Evaluation of Waste Gypsum Wallboard as a Compost Additive

by

Christopher Richards

Submitted in partial fulfilment of the requirements
for the degree of Master of Science

at

Dalhousie University
Halifax, Nova Scotia
December 2013

DEDICATION PAGE

This paper is dedicated to my wife and best friend Penny. Without her support, encouragement, understanding and occasional kick in the posterior it would never have been completed.

Thank you is not enough.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Twenty percent of all the material delivered to construction and demolition (C&D) disposal sites in the Province of Nova Scotia, Canada, is waste gypsum wallboard (WGW) (Dillon Consulting Ltd., 2006). This is typically in the form of residential or business demolition waste, which includes WGW from new construction activities. This study looked at the use of papered and de-papered waste gypsum wallboard in compost to evaluate its impact on the process, total heavy metal concentration, bioavailable metal concentration, and movement of heavy metals. The study consisted of three components: a short term mechanical in-vessel compost sub-study to assess the impact of composting WGW; a lysimeter cell sub-study to evaluate potential movement of compost constituents from compost to soil and water under a static compost system open to the ambient environmental conditions; and, a final sub-study to determine the performance of waste gypsum wallboard in compost under controlled composting conditions. The study found that the inclusion of up to 34% (by mass) WGW had no negative effects on the degradation of carbon, final pH, and final electrical conductivity in the compost product, however, WGW-containing composts did increase concentrations of total sulphur. There was the potential for elevated levels of total lead and cadmium but the compost produced was within the CCME Class A guidelines for heavy metal concentration. Waste gypsum wallboard containing composts also had increased levels of bioavailable cadmium compared to non-WGW composts.

LIST OF ABBREVIATIONS USED

BEEC	Bio-Environmental Engineering Centre
BF	Bioavailability Fraction
C&D	Construction and Demolition
CCME	Canadian Council of Ministers of the Environment
D-WGW	De-papered Waste Gypsum Wallboard
FGD	Flue Gas Desulfurization Gypsum
LSD	Least Significant Difference
NSAC	Nova Scotia Agricultural College
P-WGW	Papered Waste Gypsum Wallboard
SBR	Sequential Batch Reactor
TMEEC	Testing Methods for the Evaluation of Composting and Compost
WGW	Waste Gypsum Wallboard

ACKNOWLEDGEMENTS

I would like to acknowledge the support and advice of Dr. Gordon Price. It was through Gordon’s tireless efforts that I was finally able to begin to think and write. I would also like to thank the other members of my committee, Dr. Richard Donald and Dr. Paul Arnold for their wisdom through this process.

Special thanks go out to Mr. Cory Roberts and Mr. Doug Burris whom without their assistance and technical knowledge I would not be able to accomplish this task.

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Waste gypsum wallboard is a significant problem in North America, contributing to the amount of material that is delivered to landfills for disposal. It is estimated that 4.8 kg of wallboard waste is generated for every square meter of new construction (Mandepanda et al., 2000). In 2004, the US Geological Survey reported that 3,289 million square meters of gypsum wallboard was produced in the United States (Founie, 2006). Twenty percent of all the material delivered to construction and demolition (C&D) disposal sites in the Province of Nova Scotia, Canada, is waste gypsum wallboard (Dillon Consulting Ltd., 2006). This is typically in the form of residential or business demolition, which includes WGW from new construction activities. In the Northeastern United States, 1.2 million tonnes of WGW was generated (653,000 tonnes of new scraps and 447,000 tonnes of demolition/renovation waste) in 2006 (Northeast Waste Management Officials Association, 2010). It was also estimated that the City of Ottawa, Canada, sends 33,600 tonnes of WGW annually to landfills (Gratton and Beaudoin, 2010). Currently in Nova Scotia, WGW is not recycled and is disposed of in secure C&D landfills. In some cases, the high sulphur content of gypsum wallboard placed in landfills in combination with anaerobic conditions leads to the emission of hydrogen sulphide gases, which can become a health and environmental hazard (Flynn, 1998). To reduce this impact on available space in landfills, an alternate use for waste gypsum wallboard must be found.

1.2 LITERATURE REVIEW

1.2.1 Manufacture of Wallboard

Wallboard is one of the most widely used interior wall construction materials in North America (Gratton and Beaudoin, 2010). Typically, wallboard is sold with a white facing paper allowing for ease of finishing and painting (Certain Teed, 2011a). Wallboard is manufactured by injecting a slurry of calcined gypsum between two sheets of paper, compressing, and subsequently drying it. According to the Gypsum Association (2004), 24 different types of gypsum wallboard are available in North America ranging from 2.4 to 4.3 meters in length and with thicknesses between 6.35 mm and 25.4 mm. Traditionally, mined gypsum has been the primary source of raw material.

During the manufacturing process, different chemical additives are used. For example, adhesives are used in the paper edging (Certain Teed, 2011a); anti-fungal agents are used in wallboard that may be exposed to high moisture; and, glass fibers are incorporated in fire resistant wallboard for boilers or connecting walls (Certain Teed, 2011b). The primary regulatory concern is associated with post-consumer chemicals used in wall coverings, such as paints and wallpaper, which may contain heavy metals and contaminants.

1.2.2 Current Situation in Nova Scotia

It is estimated that approximately 20% of the material delivered to construction and demolition disposal sites is gypsum wallboard, either from new construction or renovation/demolition of buildings (Dillion Consulting Ltd., 2006). Each year approximately 200,000 tonnes of C&D waste is generated in Nova Scotia. Across many jurisdictions, wallboard residuals entering C&D sites is approximately 25% by weight of all waste (Dillon Consulting Ltd., 2006). Currently in Nova Scotia, there are no operating wallboard manufacturers that could potentially take this material to be recycled into new wallboard. As a result, the majority of this material is disposed of in secure landfills. The material placed in landfills can lead to the build up and emission of hydrogen sulphide gases under anaerobic conditions which are a health and environmental hazard (Flynn, 1998).

1.2.3 Wallboard Concerns

Waste wallboard is associated with some potential hazards and health concerns. Until lead was banned in paint in 1976 (Health Canada, 2013), the use of lead-based paints was quite common in Nova Scotia. Since some of the C&D debris is collected from older homes and buildings, there is the potential for used wallboard to contain lead. A further complicating factor in the production of new wallboard relates to the source of gypsum used in the manufacturing process. Many wallboard manufacturers are now using an industrial by-product called synthetic gypsum as the main source of gypsum for their products.

1.2.4 Flue Gas Desulfurization Gypsum (FGD)

Increased attention to industrial gas emissions has led regulatory authorities to legislate users of fossils fuels (primarily coal-fired power plants) to reduce their gaseous emissions, specifically sulphur dioxide (SO_2). A commonly employed technology is to inject a counter-current flow of misted limewater into the gaseous stream to scrub out the SO_2. The limewater reacts with the SO_2 to form a precipitate of calcium sulphate, also known as flue gas desulfurization gypsum. Flue gas desulfurization gypsum (FGD) is removed from the water for further processing. Due to the reduced temperatures required for the operation of the scrubber, some of the volatile metals (such as mercury) contained in the gas stream may condense out into the synthetic gypsum (Kairies et al., 2006; Shock et al., 2009; Tayibi et al., 2009). In the United

States, new wallboard is increasingly being manufactured from FGD (Gypsum, 2008) which could pose additional management concerns if waste wallboard is to be diverted from landfills (Lorrimore, 2009).

1.2.5 Gypsum in Agriculture

Gypsum has historically been used in agriculture as a soil conditioner to improve the soil tilth and provide calcium and sulphur for plant nutrition (Dontsova et al., 2005). Gypsum has also been observed to aid in the reclamation of saline-sodic soils (Hanay et al., 2004, Zia et al., 2007). Varcoe et al. (2010) measured a significant decrease in aqueous Ca, Mg, Mn and Na when gypsum was applied at 15,000 kg ha^{-1} in the Mount Lofty Ranges area of South Australia.

Gypsum can also be used the soil texture by flocculating fine clay particles in the soil. Clay and organic matter in the soil is negatively charged and the calcium in the gypsum in attracted to it. By combining small clay particles together opens up pores in the soil structure allowing the influx of water and root penetration (Gypsum New Zealand, 2013).

1.2.6 Waste Gypsum Wallboard Strategies

Saludes et al. (2008) reported that adding the paper from waste gypsum wallboard to cattle manure compost had no negative effects on the composting process. Wolkowski (2003) found that land application of crushed wallboard on alfalfa plots was effective as a commercial gypsum fertilizer. Marvin (2000) noted that WGW could be used as a bulking agent in compost, as a source of calcium and sulphur as micronutrients , and with the paper component supplying some carbon to the compost and acting to absorb excess moisture. Turley (1998) observed that adding crushed WGW to soil could reduce subsoil hardpans by loosening the clay in soils, allowing increased air and water circulation. While these studies have used WGW, their focus has been on material which has not been treated with post-manufacturing coatings, such as paint.

1.2.7 Composting

Composting is a natural process in which microorganism breakdown complex organic compounds into simpler forms under aerobic conditions (Rynk 1992). Microorganisms utilize oxygen, carbon, nitrogen, and many micro-nutrients, releasing energy as heat along with water vapour and carbon dioxide. The overall success of the composting process is determined by a number of factors including: a balanced carbon to nitrogen ratio, sufficient oxygen, temperature and moisture control, a pH close to neutral, adequate processing time, and a porous compost pile with good internal structure (Rynk, 1992). Table 1.1 shows the range of some important compost parameters and optimal target levels.

Table 1.1 Acceptable and Target Compost Criteria (Rynk, 1992)

Criteria	Acceptable Range	Target
Carbon to Nitrogen ratio	20:1 to 40:1	30:1
Moisture Content	40 – 65%	60%
pH	5.5 to 9.0	7.0

Oxygen needs are greatest in the early stages of decomposition and decrease as the composting process proceeds. A minimum of five percent oxygen within the compost pore spaces is needed to prevent the compost from going anaerobic (Rynk, 1992). Anaerobic conditions can lead to offensive off-gas production. Proper aeration will also ensure that heat, water vapour and gases can vacate the compost pile (Rynk, 1992).

Composting microorganisms need carbon, nitrogen, phosphorus and potassium as macro-nutrients. The availability of these nutrients will have a large impact, not only on the success of the composting process, but also on the quality of the compost produced (Rynk, 1992). Carbon is needed for energy and growth, while nitrogen is required for protein formation and reproduction. The general rule of thumb is for the total carbon concentration to be 30 times greater than the total nitrogen concentration in the mixed compost feedstocks. This ratio will be dependent on the complexity of the carbon sources. Simple carbon sources, high in sugars, will break down quickly and this ratio can be lower. Complex carbon sources, for example high concentrations of lignin, will take longer for the microorganisms to decompose, and a higher carbon to nitrogen ratio will be required. Biodegradability is also influenced by particle size; therefore, size reduction can be employed to increase the degradability of complex carbon sources (Rynk, 1992).

Moisture is required for microbial processes and a moisture content of 15% should be maintained at a minimum, but ideally between 40 and 65% (Rynk 1992) is desirable. The moisture in the compost pile provides a medium for chemical reactions, nutrient movement and microbial movement. Excessive moisture will clog the compost pile pore spaces leading to reduced aeration and anaerobic conditions. Low moisture content will cause the slowing of the composting process to the point that it halts.

The composting process consists of an initial period of biological activity which raises the temperature of the pile from ambient to about 40 °C (mesophillic), a further heating to over 60 °C (thermophillic) followed by a cooling down phase to ambient conditions during the curing phase (Dougherty 1999). A high compost pile temperature is beneficial as it will kill human pathogens (> 55°C) and destroy weed seeds (> 63°C) (Rynk 1992). As heat is generated in the pile, it will be lost due to evaporation and air movement if a proper pore space is maintained. Although heating is a sign of energy release, if the pile temperature increases to greater than

71°C, microorganisms will start dying and the composting process will stop (Rynk 1992). Turning the compost pile and/or aerating the contents can alleviate this condition.

The preferable compost pH is between 6.5 and 8 with final compost being slightly basic. As the composting process commences, there is an initial drop in pH due to the formation of organic acids. An anaerobic pile can generate ammonia which will cause an increase in pH that can negatively impact the composting process.

Compost completion time will depend on all of the previously mentioned factors. The composting method will also affect the time to maturity with passive management taking the longest and mechanical management taking the shortest. When the composting process is complete, the final product is more homogeneous and stabilized than the original feedstocks.

1.2.8 The Composting Regulatory Environment

The Canadian Council of Minister of the Environment (CCME) has issued guidelines for the classification of composts based on the concentration of trace metals and pathogens (CCME, 2005). In particular, three toxic (cadmium, mercury and lead) have been identified as having no value in plants or animals while a number of other trace metals have been defined as beneficial but these can also become deleterious at elevated concentrations. The province of Nova Scotia has adopted the same guidelines (Table 1.2) (Nova Scotia Department of Environment, 2010).

Table 1.2 Nova Scotia Department of Environment (NSDoE, 2010) Maximum Allowable Total Heavy Metal Concentrations in Composts in mg kg^{-1} Dry Weight.

Parameter	Class A	Class B
Arsenic	13	75
Cadmium	3	20
Chromium	210	1060
Cobalt	34	150
Copper	400	760
Lead	150	500
Mercury	0.8	5
Molybdenum	5	20
Nickel	62	180
Selenium	2	14
Zinc	700	1850

1.2.9 Heavy Metals in Compost

Many factors have an influence on the composting process including nutrients, moisture, oxygen, and temperature (Dougherty, 1999). These factors can also influence the binding and mobility of metals in compost and soils. Organic matter content and pH are also parameters that influence heavy metal mobility in compost. Organic matter can bind zinc, copper, chromium and cobalt, thereby making these metals unavailable to plants and organisms, and less prone to movement (Kumpiene et al., 2008; Smith, 2009; Tisdale, 1993). Cadmium, zinc, copper, lead, and nickel are made less available at increasing pH (Kumpiene et al., 2008; Smith, 2009; Tisdale, 1993) while chromium becomes more available as it is oxidized from Cr (III) to Cr (VI) (Kumpiene et al., 2008).

Total heavy metal concentrations are used for regulatory purposes but do not give the complete picture of availability. Warman et al. (1995) found that there was not always good correlation between the total heavy metal concentration in the growing media and heavy metal uptake by plants. Eneji et al. (2003) found that aerobic composting increased the level of humic acid. Humic acids can then lead to increased complexing of metal ions (Paré et al., 1999), reducing their availability to plants.

Baldwin and Sheldon (1999) and Smith (2009) reported that heavy metal cations had increased solubility with decreasing pH. Many organic materials can be contaminated with heavy metals and therefore increase the potential of leaching in the soil system if incorporated into compost (Businelli et al., 2009). This is especially true if the soil pH is low and can further increase the leachability of heavy metals (Smith 2009).

Organic matter has an important role in the availability of heavy metals as it provides sites for the adsorption on organic solids and soil particulates (Businelli et al., 2009). Chen et al. (2010) reported that dissolved organic matter can also affect the mobility of heavy metals in compost. Although heavy metals can be bound by organic matter, they do not do so at the same rate; Smith (2009) reported that this differential order in rate of binding was Pb>Cd=Cu>Zn. Greenway and Song (2002) reported that this order was Pb>Cr>Cu>Ni≥Cd≥Zn with respect to binding to humic acid, and went on to suggest that humid acid was the primary organic matter binding site. Heavy metals also tend to concentrate as compost ages due to the loss of mass through carbon mineralization, respiration and loss of volatile elements (Enji, 2003; Farrell and Jones, 2009).

1.2.10 Composting Using Waste Gypsum Wallboard

Many of the existing studies have looked at alternate uses of new gypsum wallboard, but there has been little work to date on using mixed wallboard (new and used) as a compost additive. Most disposal sites receive a mixture of new and waste gypsum wallboard, both of which could possibly be added to compost instead of landfilled; a valuable resource could be converted into a value-added product and reduce the demand on valuable landfill space.

Prior to this becoming practice however, a number of questions will have to be answered. How will the addition of this material affect the composting process? Will the addition of WGW to compost require some special management practices to ensure that the product produced is suitable for the intended use? What is the concentration of heavy metals in WGW and will this have an effect on the heavy metal concentration of the compost produced? Will the heavy metals in WGW compost leach out into the soil and /or water? Are the heavy metals in WGW compost bioavailable to plants? The following study will attempt to answer many of these questions.

1.3 OBJECTIVES

The objectives of this study were:

- To quantify the concentration of heavy metals in WGW and WGW composts
- To examine the mobility and bioavailability of heavy metals when using WGW as a compost additive.
- To evaluate the characteristics of compost when using WGW as an additive. Specifically, the impact of the addition of WGW on compost pH, electrical conductivity, total carbon, total nitrogen, and the compost temperature profile over time.

These objectives were met through three sub-studies as will be detailed in this thesis. The first sub-study (as detailed in Chapter 2) involved the use of an in-vessel mechanical composter over a six week period to produce two composts; one with WGW addition and another without WGW addition. The composts produced were tested for total and bioavailable heavy metals as well as various composting parameters.

To further investigate the results from the in-vessel sub-study, a second sub-study (discussed in Chapter 3) looked at the total concentration and mobility of heavy metals in compost with the use of lysimeter cells. Three compost treatments where prepared; without WGW addition (control), WGW addition, and WGW addition with the paper removed. The compost was placed over a layer of soil and exposed to the environment. Water that drained through the compost and soil was collected and quantified. Compost treatments and underlying soils were tested for total and bioavailable metals at the beginning and end of the sub-study. Leachate was tested for soluble metals at each sampling date as determined by water flow through the cell.

The final sub-study, as discussed in Chapter 4, focused on the influence of WGW on the composting process. While the lysimeter sub-study looked at heavy metals in compost, the compost piles were static in nature and not a true indicator of compost performance. In the final sub-study, two compost treatments, with and without WGW, were prepared and placed in covered bins then managed for approximately a year. The treatments were turned periodically and moisture content adjusted if required. To determine if there was any influence of WGW addition; the compost treatments were evaluated at intervals over the term of the sub-study.

CHAPTER 2 IN-VESSEL COMPOSTING STUDY

2.1 INTRODUCTION

Gypsum has been used in agriculture as a soil conditioner to improve the soil tilth and provide calcium and sulphur for plant nutrition (Dontsova et al., 2005). Varcoe et al. (2010) measured a significant decrease in aqueous Ca, Mg, Mn and Na when gypsum was applied at 15,000 kg ha^{-1} in the Mount Lofty Ranges area of South Australia. Turley (1998) observed that adding crushed WGW to soil could reduce subsoil hardpans by loosening the clay in soils allowing increased air and water circulation. Further work by Wolkowski (2003) found that land application of crushed wallboard on alfalfa plots was effective as a commercial gypsum fertilizer. Gypsum has also been observed to aid in the reclamation of saline-sodic soils (Hanay et al., 2004, Zia et al., 2007). Limited research has been conducted on gypsum in compost systems.

Saludes et al. (2008) reported that using the paper from waste gypsum wallboard in cattle manure compost had no negative effects on the composting process. Moreover, Marvin (2000) noted that WGW could be used as a bulking agent in compost, providing calcium and sulphur as micronutrients with the paper component supplying some carbon to the compost, and acting to absorb excess moisture. While these studies have used WGW in soils or composts, the focus has been on unadulterated material which has not been treated with post manufacturing coatings, such as paint.

The objective of this first study was to determine the feasibility of using WGW as a compost additive. This study also examined the impact on heavy metal concentrations, both total and bioavailable, in compost when WGW is added to compost. The information generated in this study was used as a basis for the design of further studies. To accomplish these objectives, two treatments of compost were prepared: one consisting of untreated Class B biosolids and straw while the other consisted of untreated Class B biosolids, straw, and crushed WGW, using an in-vessel composter over a six-week period. Compost samples were collected and analyzed for composting parameters and concentration of heavy metals (total and bioavailable). The WGW consisted of both new material from construction sites and used material from demolition/renovation projects. The WGW was added at 40% by weight to the WGW treatment.

2.2 MATERIALS AND METHODS

The following section outlines the materials used, protocols followed, and parameters measured in the study.

2.2.1 In-Vessel Composter

The in-vessel composter used for this study is located at the Bio-Environmental Evaluation Centre (BEEC) in Bible Hill, Nova Scotia, Canada (Lat 45.39, Long -63.24). This device has a total compost capacity of 365 L. It is constructed of a stainless steel U-shaped chamber with a removable cover (Figure 2.1). The device is equipped with an internal mixer consisting of a central shaft with four equidistantly placed mixing paddles. The central shaft is powered with a variable frequency electrical drive that allows for mixing speed control. The shaft speed is set and maintained with electrical controls. For this study, the in-vessel composter was kept running at a slow speed (approximately two revolutions per minute) for the duration of the study. The composter is equipped with a small electrically controlled exhaust fan to remove odors through a port in the cover. The composter has a water jacket for temperature control (not used for this study) and rigid foam insulation to slow the loss of internal heat.

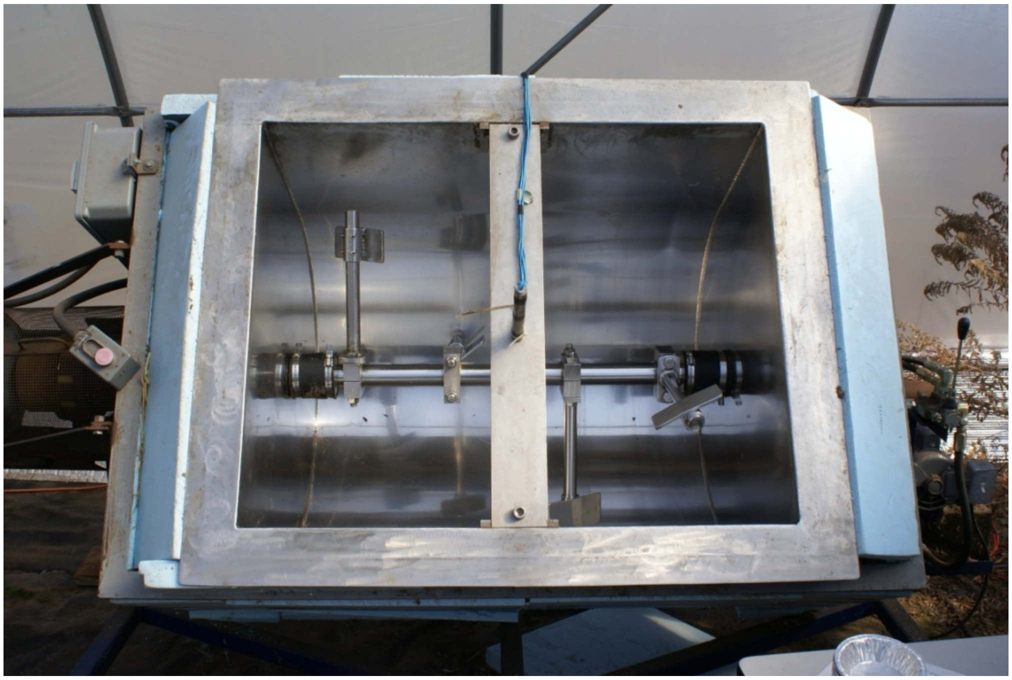

Figure 2.1 In-Vessel Composter

2.2.2 Compost Feedstocks

Three feedstocks were used to prepare the compost treatments for this study: barley straw, Class B biosolids from a Sequential Batch Reactor (SBR) system (from Colchester County Waste Treatment Facility), and crushed WGW. The WGW was obtained from Halifax C&D Recycling Ltd. located in Goodwood, Nova Scotia, Canada. This facility receives construction and demolition (C&D) waste from the greater Halifax area, including WGW. The WGW was a combination of new construction scraps and material from building demolitions and /or home renovations. The WGW used for this study had all foreign objects (nails, screws, etc.) removed and was crushed using a plate grinder to less than 9 cm. No paper was removed from the WGW for this study. Samples of all feedstocks were collected and analyzed prior to mixing of compost constituents.

2.2.3 Experimental Design

The study consisted of two treatments, one without crushed WGW and one with crushed WGW. The in-vessel compost trials were run for six weeks each, and samples were collected at weekly intervals. Each compost treatment filled approximately one half of the volume of the composter (WGW 100 kg, control 68 kg) when it was initially prepared.

2.2.4 Compost Recipe and Preparation

The goal was to generate two compost treatments with a carbon:nitrogen ratio of 27:1 and a target moisture content of 60%. Table 2.1 outlines the calculated feedstock ratios as per the compost design for the two treatments. Compost feedstocks were individually weighed into a plastic tote using a floor scale then placed into the composter. The compost mixer was started prior to the addition of feedstocks to aid in mixing the ingredients as they were introduced.

Table 2.1 In-Vessel Compost Design Formulations.

Compost Formulation	Raw Feedstocks (% by Dry Mass)		
	Biosolids	**Wallboard**	**Straw**
#1 WGW	40	40	20
#2 Control	64	0	36

2.2.5 Monitoring and Sampling

At each sampling (weekly), six samples of approximately one kilogram each were collected across the length of the composter. Samples were placed in labeled plastic bags, and tightly sealed until required for testing.

2.2.6 Analytical Methods/Analysis

Feedstock and compost samples were tested and analyzed following standard methods.

Samples collected each week were tested for moisture content by placing a representative subsample (approximately 50 g) in an oven at 105°C oven and drying to constant weight (Carter, 1993).

Samples for carbon and nitrogen content analysis were dried in a moisture oven at 60°C until constant weight was obtained. Dried samples were chopped using a Waring blender (Waring Products, Torrington, CT, USA), and then ground using a Retsch MM300 ball mill (Retsch GmbH & Co. KG, Haan, Germany). All ground samples were stored in vials until required for testing.

Total nitrogen and total carbon content of all samples were determined on the ground samples using a Leco CN-2000 (Leco Corporation, St. Joseph, Michigan, U.S.A.) using the manufacturer's analytical method for plant material (Leco Corporation, 2010a). The instrument was run according to the manufacturer's recommendations for plant materials. To ensure that that the instrument was running in a stable state, sample blanks were run until constant readings were obtained. The instrument was then calibrated with certified EDTA. Once a calibration curve was prepared, the samples (approximately 0.5 g) were run with periodic certified alfalfa samples to check for drift of the calibration curve.

Samples for metal content determination were dried in an oven set at 36°C until constant weight was obtained. These samples were dried at a lower temperature (compared to the normal temperature of 60°C) to ensure that any mercury in the samples was not vapourized through the drying process. This is the official method for compost analysis as defined by the Composting Council Research and Education Foundation (2002) in their Test Methods for Examination of

Composting and Compost (TMECC). Once the samples reached constant weight they were ground using a Retsch MM300 ball mill (Retsch GmbH & Co. KG, Haan, Germany) to < 2 mm. All samples were stored in vials until required for testing.

Total heavy metals (except mercury) were determined using the TMECC method 04.12-B for nitric acid digestion of compost and soils (TMECC, 2002). Approximately one gram samples, weighed to the nearest 0.0001 grams using an analytical balance, were added to digestion tubes and acid-digested with a block digester. Samples were filtered into 100 mL volumetric flasks, made to volume and tightly sealed.

Total mercury was extracted from all samples using an acid digestion method using a block digester. The method used was a Standard Operating Procedure (SOP) developed by the NSAC Environmental Sciences Department for the extraction of mercury in tissue samples. Once digestion was complete samples were filtered into 100 ml volumetric flasks, brought to volume and tightly sealed. Bioavailable metals were determined using the ground compost samples and a Mehlich III extraction method (Carter, 1993).

All sample extractions were stored in a refrigerator at 4°C until day of testing. On the day of testing, sample extractions were warmed to room temperature by placing them on a bench-top prior to analysis.

Total and bioavailable metal concentrations were measured on digested filtrates using a Varian 240FS Fast Sequential Atomic Absorption Spectrometer (Agilent Technologies, Santa Clara, CA, U.S.A.) equipped with a Varian SIPS 10/20 Sample Introduction Pumps System. The instrument was calibrated using multi-element 10 ppm and 100 ppm standards prepared by Plasma-Cal (Plasma-Cal, Baie D'Urfe, Quebec, Canada). The instrument was operated according to the manufacturer’s recommended settings. The metals were analyzed according to the parameters listed in Table 2.2.

Table 2.2 Varian AA240FS Settings for Individual Metals

Heavy Metal	Fuel	Auxiliary Equipment
Chromium	Acetylene/Air	SIPS
Cobalt	Acetylene/Air	SIPS
Cadmium	Acetylene/Air	SIPS
Nickel	Acetylene/Air	SIPS
Lead	Acetylene/Air	SIPS
Copper	Acetylene/Air	SIPS
Zinc	Acetylene/Air	SIPS
Molybdenum	Nitrous Oxide/Acetylene	SIPS
Selenium	Cold Vapour, Acetylene/Air	Hydride Generator
Mercury	Cold Vapour	Hydride Generator

All metals were analyzed using the multi-element standards except for molybdenum, mercury, and selenium where single metal standards were used. A single element mercury standard was used for calibration in concentrations of 50, 100, and 250 parts per billion (ng L^{-1}). Mercury samples were diluted at a five-to-one ratio prior to analysis to bring the samples within the range of the standards.

Total mercury and selenium were analyzed using a Varian AA240FS (Fast Sequential Atomic Absorption Spectrometer) equipped with a Varian VGA-77 vapour generator as per the manufacture’s recommendations. The cold vapour cell was placed in the lamp pathway and a 45 second delay was employed to ensure the cell was fully saturated with the sample vapour before readings were recorded.

2.2.7 Statistical Analysis

Data was analyzed using Minitab for descriptive statistics and SAS/STAT v. 9.3 (SAS Institute Inc., 2010) PROC GLM ANOVA for CRD employing the Tukey test for mean comparisons; significant differences were considered at the $P<0.05$ probability level.

2.3 RESULTS

The following sections outline the results of analytical testing of samples collected during this study, as well statistical analyses of the resulting data.

2.3.1 Feedstock Analysis

The compost feedstocks were analyzed for total carbon content, total nitrogen content, and moisture content prior top preparation of compost mix designs. The results of these analyses are presented in Table 2.3. The moisture content of the WGW was higher than expected due to storage of this feedstock outside by the supplier.

Table 2.3 Moisture Content, Total Carbon Content (d.w. basis), Total Nitrogen Content (d.w. basis), and Carbon to Nitrogen Ratio of Feedstocks

Raw Material	Moisture Content,%	Total Carbon† %	Total Nitrogen† %	C:N Ratio
Biosolids	89.90	35.02	6.61	5.3
WGW	46.71	4.48	0.03	147
Straw	22.44	42.63	0.35	122

† Dry mass basis

The two compost treatments had C:N ratios of 27:1 which was the design value. The control treatment had a higher initial moisture content at 65.6%, while the WGW treatment at 59.1% was closer to the designed moisture content of 60% (Table 2.4).

Table 2.4 In-Vessel Compost Treatments Feedstock Ratios, C:N Ratio, and Moisture Content

Compost Treatment	Raw Materials, %			C:N Ratio	Moisture Content, %
	Biosolids	Wallboard	Straw		
Design				27:1	60
WGW	40	40	20	27:1	59.1
Control	64	0	36	27:1	65.6

From Table 2.5 it can be seen that there are some similarities and as well as some major differences between the total heavy metal concentrations for the three compost feedstocks. These similarities and differences are more evident in the graphical display of the data in Figures 2.1 and 2.2. Biosolids have the highest concentration of zinc, copper and mercury. Waste gypsum wallboard has the highest cadmium, cobalt and lead concentrations. Straw has the highest concentration of molybdenum.

Table 2.5 Total Heavy Metal Concentrations of Raw Materials

	Heavy Metal Concentration (mg kg^{-1})†¥									
Feedstock	**Cd**	**Zn**	**Cu**	**Cr**	**Co**	**Ni**	**Pb**	**Se**	**Mo**	**Hg**
Biosolids	1.8	440	434	24.8	5.7	9.5	52.5	1.8	nd	2.7
WGW	6.2	57.5	15.3	6.4	11.5	9.3	63.9	1.8	nd	0.6
Straw	1.5	11.3	4.8	26.5	6.7	nd	13.0	1.8	3.7	0.1

† Dry weight basis
¥ nd indicates metal concentration was below detection limit

These differences are better explained in Table 2.6 which shows the results of Least Significant Difference (LSD) analysis for significance between the metal concentrations of the raw materials. The letters signify significant difference between the means of the raw materials. The letter A is assigned to the material(s) with the highest means followed by B and C. If two or more materials have the same letter,this signifies that there is no significant difference between the means of these materials. In Figures 2.1 and 2.2 the metal concentration data are compared to the Province of Nova Scotia limits for composts and municipal biosolids under Class A. This class is significant because Class A composts and biosolids have unrestricted use. Compost and biosolids that do not meet these limits are reduced to Class B and their use is restricted; biosolids used for these experimental purposes exceed the Class A concentration limits for copper and mercury and thus are deemed Class B. Wallboard exceeds the concentration limit for cadmium, while straw does not exceed any of the heavy metal concentration limits. It should be noted that all three materials come close to exceeding the limit for selenium.

Table 2.6 Results of LSD Significance Tests of Means

Heavy Metal	Biosolids	Wallboard	Straw
Cadmium	B	**A**	B
Zinc	**A**	B	C
Copper	**A**	B	C
Chromium	**A**	B	**A**
Cobalt	C	**A**	B
Nickel	**A**	**A**	B
Lead	B	**A**	C
Selenium	**A**	**A**	**A**
Molybdenum	B	B	**A**
Mercury	**A**	B	B

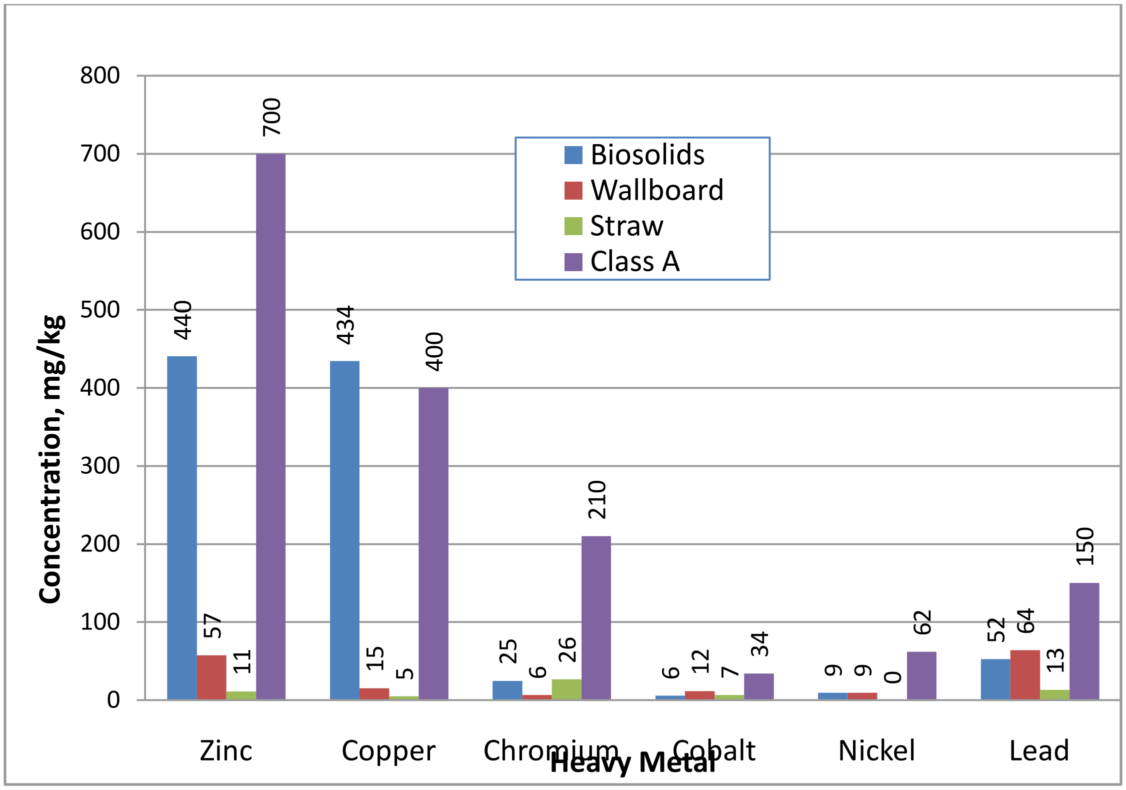

Figure 2.1 Raw Material Total Heavy Metal Concentrations of Zn, Cu, Cr, Co, Ni and Pb

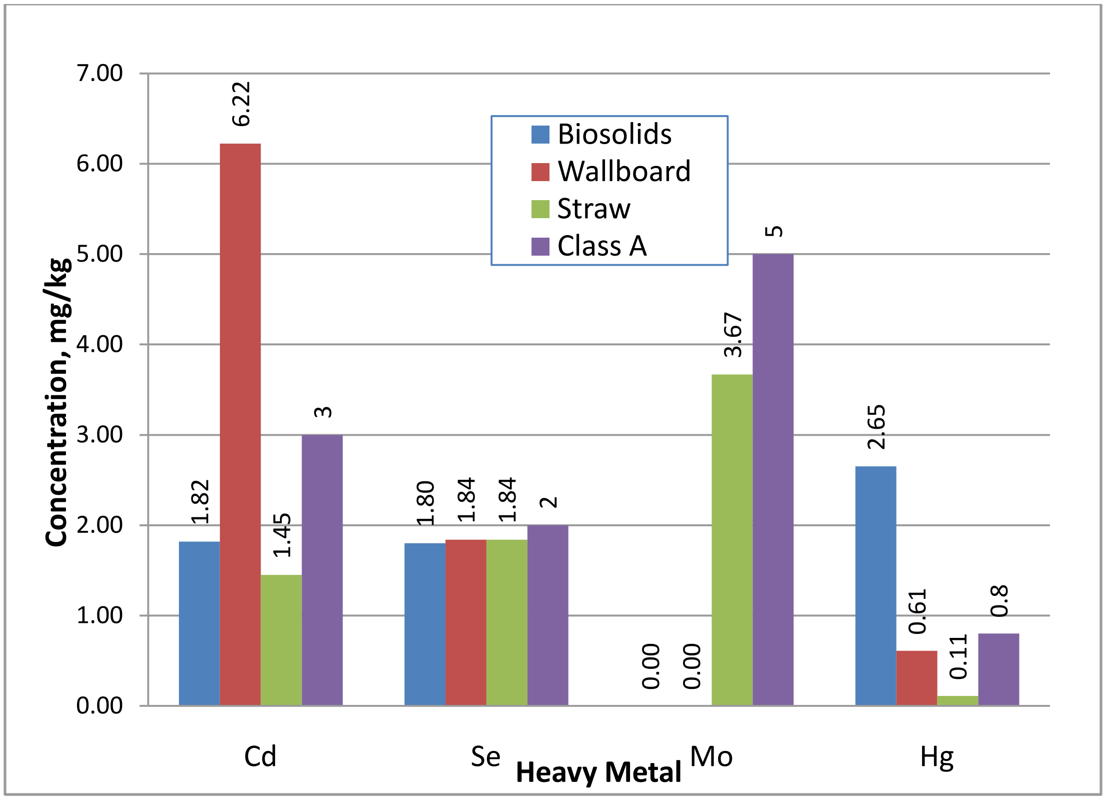

Figure 2.2 Raw Materials Total Heavy Metal Concentrations of Cd, Se, Mo and Hg

2.3.2 Moisture Content

During the six-week composting process, the moisture content of the WGW treatment was stable (Figure 2.3) until the final two weeks where there was a steady decline. This decline was also evident (although earlier) in the control treatment (Figure 2.4); at week four, the moisture was increased with the addition of water. The in-vessel composter drive mechanism failed due to a power failure during the first week of the control treatment run (therefore no sample was collected) and was not immediately detected.

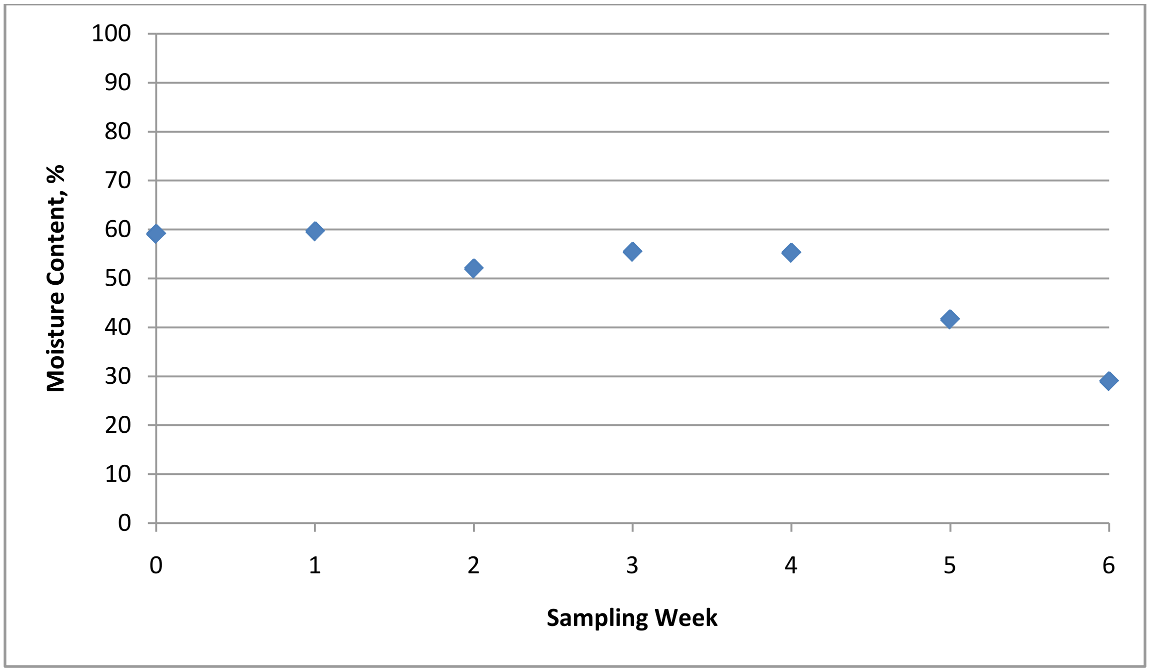

Figure 2.3 WGW Compost Treatment Moisture Content at Weekly Sampling Periods

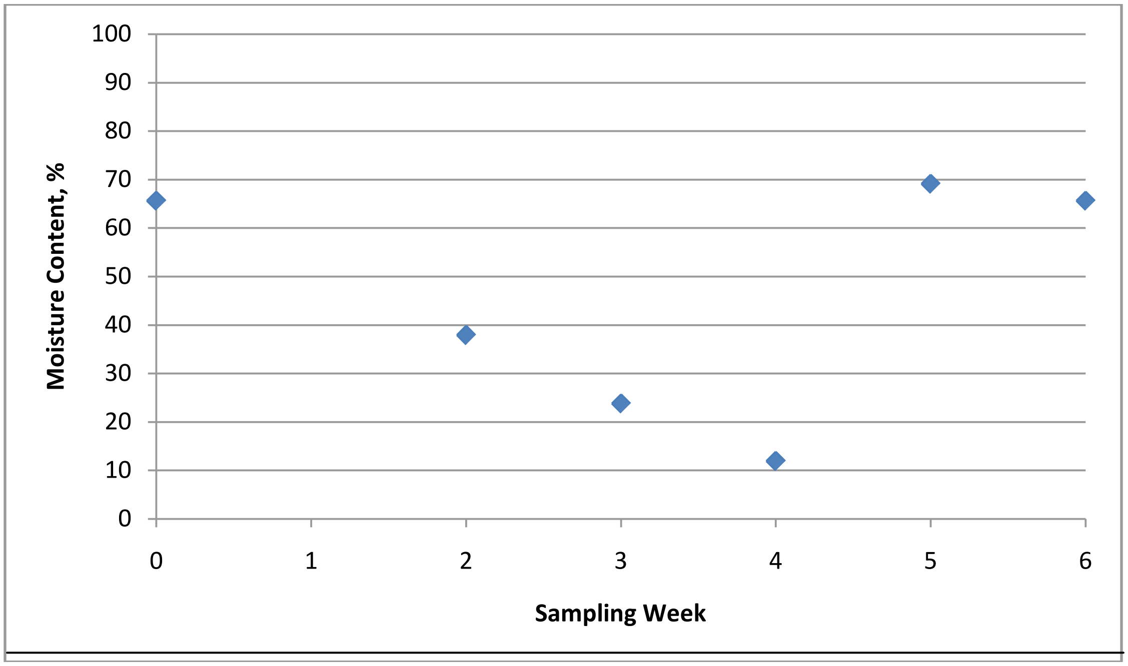

Figure 2.4 Control Compost Treatment Moisture Content at Weekly Sampling Periods

2.3.3 Total Carbon and Total Nitrogen

During the composting process, microorganisms consume carbon as an energy source, therefore, a reduction of total carbon is expected as the compost ages. Both of these mixes exhibited the expected result as can be seen in Figures 2.5 and 2.6. The reduction in both treatments was gradual in both composts with the leveling off after week 5. It should be noted that the WGW compost had a lower overall total carbon content due to the mineral content (gypsum) to begin with. By the end of the experiment, the control and WGW composts had lost 16.8% and 28.4% (based on percent total carbon in the composts) of their initial carbon, respectively.

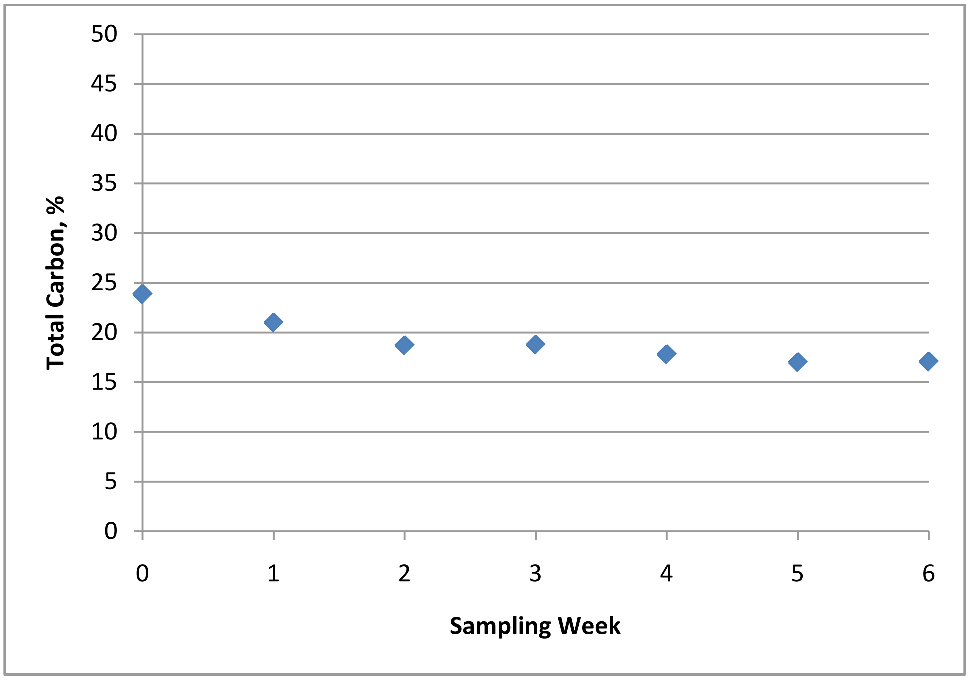

Figure 2.5 WGW Compost Total Carbon at Weekly Sampling Periods

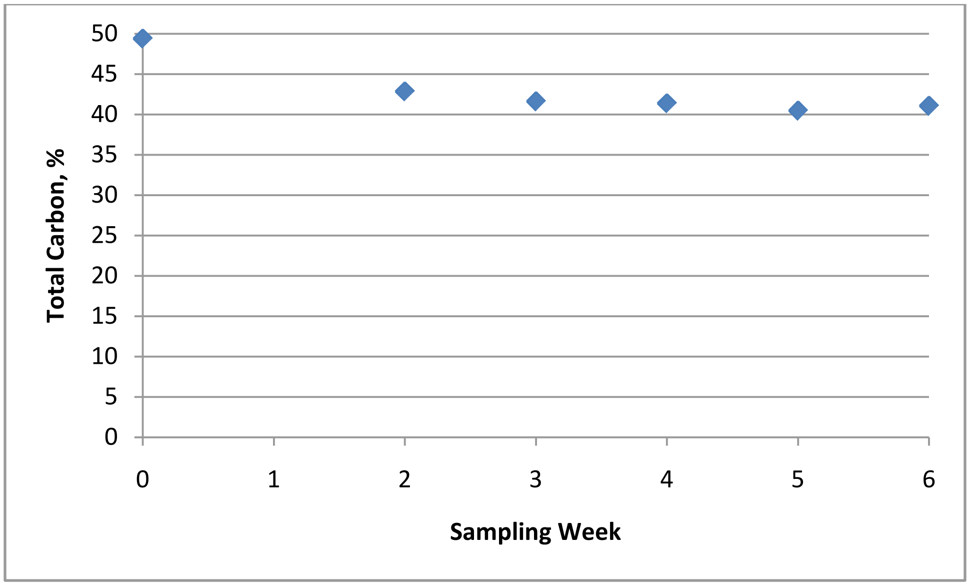

Figure 2.6 Control Compost Total Carbon at Weekly Sampling Periods

The total nitrogen (Figure 2.7) content of the WGW compost increased then declined over the final two weeks. The nitrogen content of this compost was in a narrow range (0.8 to 0.87 %) over the study period. The control compost (Figure 2.8) saw a slight increase over the length of the trial as would typically be expected as the compost

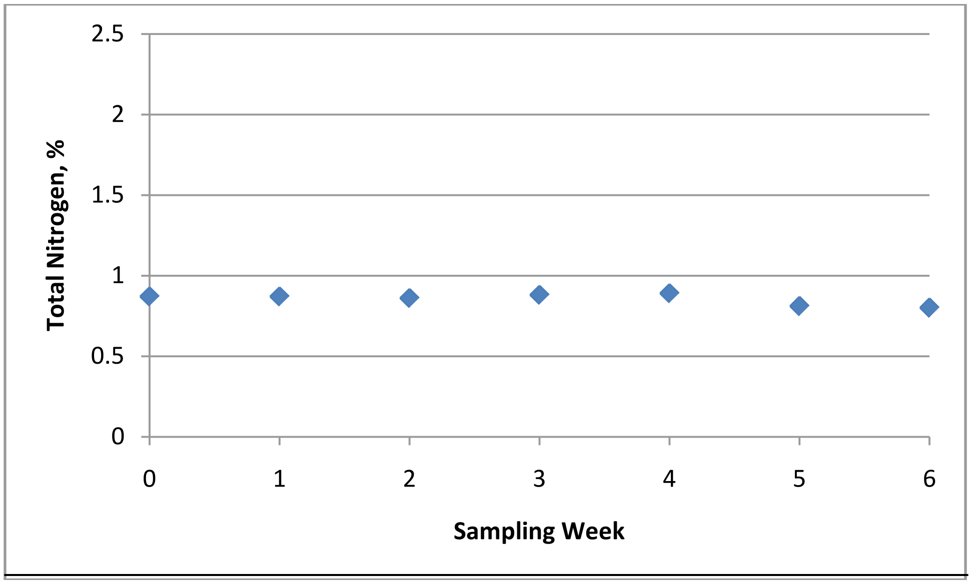

Figure 2.7 WGW Compost Total Nitrogen at Weekly Sampling Periods

experiences a disproportionate reduction in mass and concentration of the constituents. The nitrogen content of the WGW compost was less than half of the control compost due to the presence of the WGW.

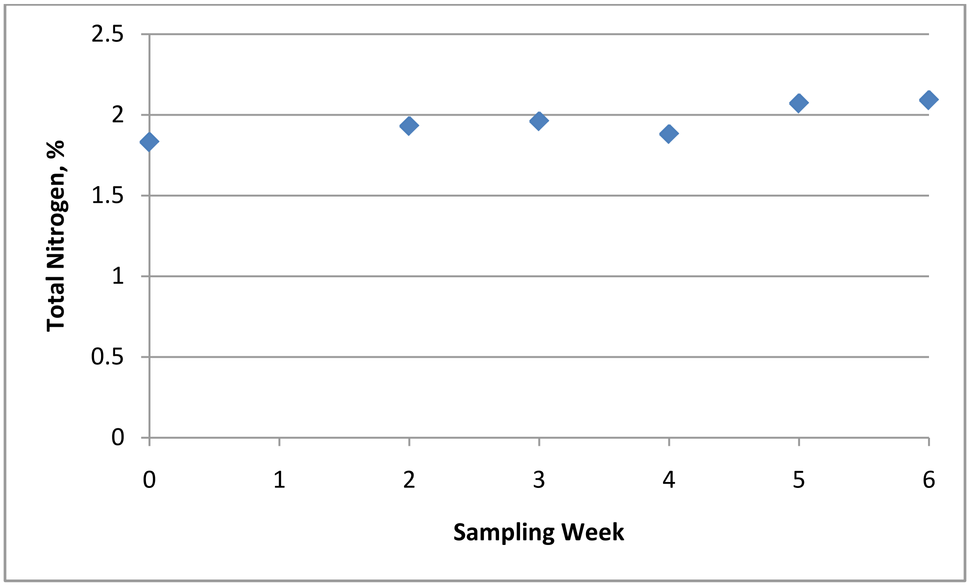

Figure 2.8 Control Compost Total Nitrogen at Weekly Sampling Periods

The carbon to nitrogen ratio reduction trends for both treatments are presented in Figures 2.9 and 2.10. Both treatments experienced a rapid reduction in the initial two weeks, followed by small or no reduction until the end of the study period.

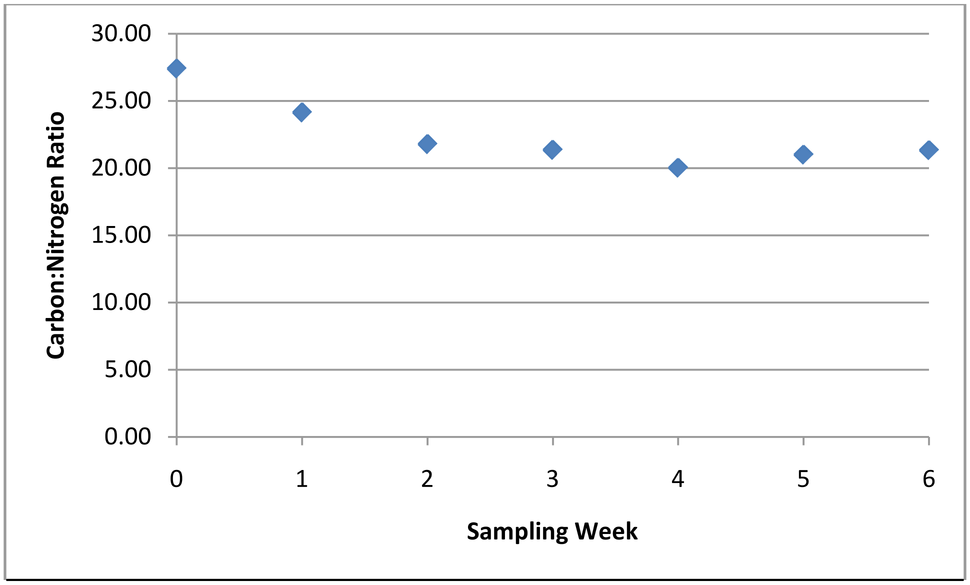

Figure 2.9 WGW Compost Total Carbon:Nitrogen Ratio at Weekly Sampling Periods

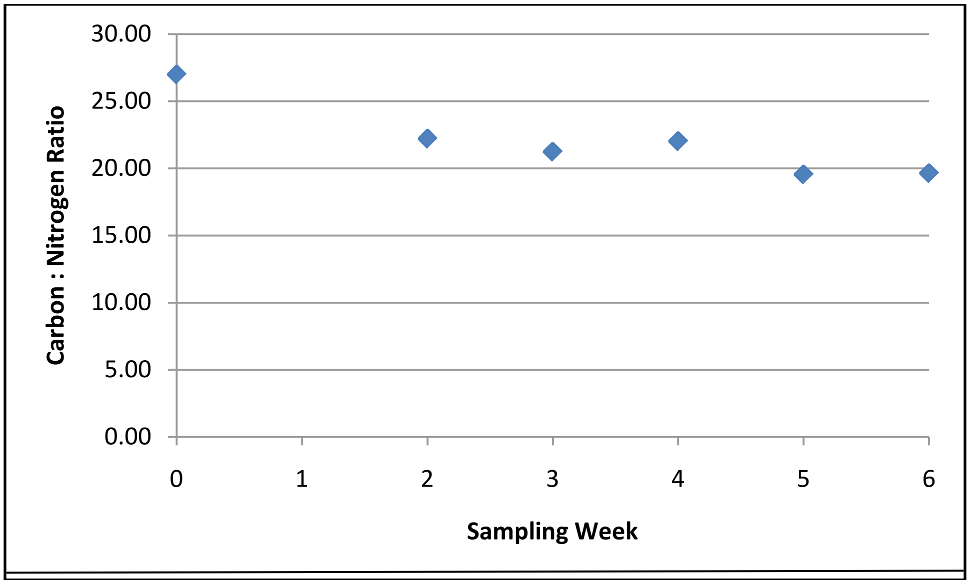

Figure 2.10 Control Compost Total Carbon:Nitrogen Ratio at Weekly Sampling Periods

2.3.4 Total Heavy Metals

At the third and sixth weeks of the study the composts were analyzed for total and bioavailable heavy metal content. Total heavy metal concentration results are presented in Table 2.7. The control compost was higher in the concentrations of zinc, copper, chromium, and nickel.

While these heavy metals were lower in the WGW compost, most likely due to the reduction in biosolids content with its higher concentration of these heavy metals, there was an increase in cadmium and lead concentrations.

Table 2.7 Three and Six Week Compost Treatment Total Heavy Metal Concentrations and CCME Class A and Class B Guidelines

				Heavy Metal Concentration (mg kg^{-1})†						
Treatment	**Cd**	**Zn**	**Cu**	**Cr**	**Co**	**Ni**	**Pb**	**Se**	**Mo**	**Hg**
Week Three										
Control	1.9	293	274	24.4	2.0	16.4	22.4	1.8	1.3	1.8
WGW	3.3	225	166	18.7	7.9	10.4	49.3	1.8	0.6	1.5
Week Six										
Control	1.7	286	280	25.1	5.9	20.1	24.3	1.8	1.3	1.7
WGW	3.5	201	181	18.3	8.3	7.9	48.6	1.8	0.7	1.3
CCME										
Class A	3	700	400	210	34	62	150	2	5	0.8
Class B	20	1850	¥	¥	150	180	500	14	20	5

† Dry weight basis

¥ No maximum limit has been set for Class B copper and chromium concentrations

Table 2.8 presents the results of the Tukey's comparisons of the two compost treatments heavy metals concentrations test results. Capital letters indicate significant differences between weeks three and six for the same treatment. Lower case letter indicate significant differences between treatments at the same testing age. For example, reviewing the cadmium results for the control treatment, the analysis resulted in an A at three-weeks and a B at six-weeks indicating that the results for week three was significantly different compared to week six. Also reviewing cadmium analysis results, the result for between treatment analysis at three-weeks yielded an a for the WGW treatment and a b for the control treatment indicating the two treatments had significantly different total cadmium concentrations at the three-week sampling.

Table 2.8 Three and Six Week Compost Treatment Total Heavy Metal Tukey's Comparisons†

	Tukey's Comparison Results									
Treatment	**Cd**	**Zn**	**Cu**	**Cr**	**Co**	**Ni**	**Pb**	**Se**	**Mo**	**Hg**
Week Three										
Control	Ab	Aa	Aa	Aa	Bb	Ba	Ab	Ba	Aa	Aa
WGW	Aa	Ab	Bb	Ab	Aa	Ab	Aa	Aa	Ab	Aa
Week Six										
Control	Bb	Aa	Aa	Aa	Ab	Aa	Ab	Aa	Aa	Ba
WGW	Aa	Bb	Ab	Ab	Aa	Bb	Aa	Aa	Ab	Aa

† Capitalized letters indicate significant differences between week three and week six results for the same treatment. Lower case letters indicate significant differences between treatments at the same sampling period.

2.3.5 Bioavailable Heavy Metals

Bioavailable metals concentrations were assessed on both compost treatments at three and six weeks (Tables 2.9 and 2.10). For the control treatment, there was not a significant difference in the bioavailable heavy metals concentrations at weeks three and six for zinc, copper, chromium, cobalt, and lead. The bioavailable concentrations of cadmium and nickel were higher at three weeks than six weeks in the control treatment. In the WGW treatment, bioavailable concentrations of all metals except chromium were not significantly different between the third and sixth week sampling periods. Bioavailable chromium was higher at the six-week period compared to the three-week period in the WGW treatment.

At three weeks the bioavailable concentration of chromium, cobalt and nickel were similar for two treatments. The bioavailable zinc concentration was double in the control treatment compared to the WGW wallboard treatment. The concentration of bioavailable copper was 1.7 times higher in the control treatment compared to the WGW treatment. The WGW treatment had double the concentration of bioavailable cadmium and 1.5 times the concentration of bioavailable lead as in the control treatment.

At six weeks the bioavailable concentration of cadmium, cobalt and nickel were similar for the two treatments. The bioavailable zinc concentration was double in the control treatment compared to the WGW wallboard treatment. The concentration of bioavailable copper was 1.5 times higher in the control treatment compared to the WGW treatment. The WGW treatment had 1.6 times the concentration of bioavailable chromium and 1.5 times the concentration of bioavailable lead as in the control treatment.

Table 2.9 Three and Six Week Compost Treatment Bioavailable Heavy Metal Concentrations

	Heavy Metal Concentration (mg kg^{-1})†						
Treatment	**Cd**	**Zn**	**Cu**	**Cr**	**Co**	**Ni**	**Pb**
Week Three							
Control	0.2	96.1	36.0	2.4	1.0	4.4	8.5
WGW	0.4	47.0	20.7	2.7	1.1	4.4	11.7
Week Six							
Control	0.4	96.2	34.9	2.1	1.0	4.1	8.5
WGW	0.4	50.6	20.4	3.4	1.3	4.3	13.1

† Dry weight basis

Table 2.10 Three and Six Week Compost Treatment Bioavailable Heavy Metal Tukey's Comparisons

	Tukey's Comparison Results†						
Treatment	**Cd**	**Zn**	**Cu**	**Cr**	**Co**	**Ni**	**Pb**
Week Three							
Control	Ab	Aa	Aa	Aa	Aa	Aa	Ab
WGW	Aa	Ab	Ab	Ba	Aa	Aa	Aa
Week Six							
Control	Ba	Aa	Aa	Ab	Aa	Ba	Ab
WGW	Aa	Ab	Ab	Aa	Aa	Aa	Aa

† Capitalized letters indicate significant differences between week three and week six results for the same treatment. Lower case letters indicate significant differences between treatments at the same sampling period.

2.4 DISCUSSION

The following section provides a discussion of the analytical results presented in the previous section through an analysis of the constituent-comparisons between feedstocks and the composting treatments.

2.4.1 Feedstocks

The biosolids were the prime source of nitrogen while at the same time having a very low (slightly more than 10%) solids content. This necessitated using straw which is a low moisture/high carbon feedstock. The WGW had a carbon content of 4.48% mainly from the paper coating. The moisture content of the WGW was high due to its storage outside at the time of sourcing.

The total heavy metals concentrations of the feedstocks would obviously influence the heavy metal concentration of the compost treatments. The higher concentrations of zinc, copper, chromium, and mercury in the biosolids would have a greater influence on the concentration of these heavy metals in the control treatment. The higher concentrations of cadmium, cobalt, and lead in the WGW would have a greater influence on the concentration of these heavy metals in the WGW treatment.

2.4.2 Moisture Content

The WGW treatment had fairly consistent moisture content until the final couple of weeks when there was a decline. The control treatment experienced a rapid decline in moisture content early in the study. The drop in the control treatment may have been due to the time of year of testing. The in-vessel composter was situated in a poly-greenhouse and this run was conducted during the early spring of the year compared to the WGW compost which was produced during the winter. Due to this, the greenhouse would have experienced higher temperatures that would have accelerated the drying of the compost. This evaporative moisture loss would have been accompanied with moisture loss due to the composting process. The in-vessel composter was equipped with an exhaust fan to remove any odors that developed. The combination of these factors could have been the cause of the rapid drying out of the compost. When the low moisture content was finally realized (by checking the compost with a hand squeeze test), the moisture content was increased with the addition of water. Too much water was added which then resulted in a moisture content higher than desired. The loss of moisture could have impacted the composting process, as studies by Liang et al. (2003) found that microbial activity increased under higher moisture contents especially in the 30% to 60% range.

2.4.3 Carbon and Nitrogen Contents of Composts

During the composting process organic components are degraded by microorganisms. This degradation results in the reduction of total carbon content of the compost mixture therefore this is one measure of the influence of a component on the composting process. In this study both of the treatments experienced a reduction in the total carbon content. The WGW compost with its lower initial total carbon content still recorded a reduction.

Overall the WGW treatment had a larger carbon reduction at 28% compared to 17% in the control treatment. This may have been due to the lower moisture content of the control treatment during the early part of the study. Khan et al. (2009) found that moisture content is one of the prime factors involved in compost systems. With the lower moisture content the degradation of composting mass was impacted and resulted in a lower carbon degradation value for the control treatment. With a lower total carbon content, the WGW compost would experience a much larger percent change with a smaller carbon reduction.

Preservation of nitrogen and an overall increase in the nitrogen concentration through volume and/or mass reduction of the compost as it ages are desirable. Neither compost treatments experienced a reduction in total nitrogen concentration although the WGW treatment did not record a significant increase as did the control treatment.

2.4.4 Total and Bioavailable Heavy Metals

The addition of WGW to the compost did appear to cause an increase in the heavy metal concentration of cadmium and lead compared to the control treatment. This increase in lead content was also reflected in the bioavailable lead in the WGW treatment compared to the control treatment but did not to appear to impact on bioavailable cadmium. Comparing the concentration of bioavailable metals vs. the total metals, although the total concentration of lead in the WGW treatment was higher than the control treatment, only 27% of the lead was bioavailable compared to 35% for the control treatment. Smith (2009) found that compost had a high affinity to bind lead into stable forms and sulphide fractions had even lower availability. The gypsum (calcium sulphate) component of the WGW treatment appears to have influenced the bioavailability of lead. The ratio of bioavailable to total zinc was also lower in the WGW treatment than the control treatment (25% vs. 33%). These differences may be attributable to the differences in decomposition of the two treatments. This is in contrast to studies by Smith (2009), Greenway and Song (2002), and Kumiene (2008) who reported that zinc is more labile in compost and therefore the bioavailability in compost is high. It would be expected that the WGW treatment with its higher carbon degradation would have a higher bioavailable zinc concentration.

2.5 CONCLUSION

Overall, there did not appear to be any hindrance to the composting process with the 40% addition by dry mass of WGW as this compost did experience a reduction in total carbon content, in fact higher than the control compost (19% vs. 13% in the control). There was some concern about the potential higher concentrations of total cadmium and lead in the final WGW compost but this could be controlled through reducing the WGW content. The higher total concentration of cadmium in the WGW however did result in a higher concentration of bioavailable cadmium than the WGW treatment. The inverse was found for bioavailable chromium with the control treatment having a higher total concentration of chromium while the WGW treatment had a higher concentration of bioavailable chromium.

The information gathered in this study was further explored in the next study. The in-vessel composter, while it did produce compost, was of small volume and uninfluenced by outside factors such as weather. The next study was conducted to verify the heavy metal results from the in-vessel study while adding a leaching dimension to the equation. A larger volume of compost was used that was subjected to outdoor environmental conditions. The potential movement of metals could therefore be studied as well as some important composting parameters such as pH, electrical conductivity, and temperature profiles.

CHAPTER 3 LYSIMETER CELL STUDY

3.1 INTRODUCTION

Wallboard is one of the most widely used interior wall construction materials in North America (Gratton and Beaudoin, 2010). Typically, wallboard is sold with a white facing paper allowing for ease of finishing and painting (Certain Teed, 2011a). Wallboard is manufactured by injecting a slurry of calcined gypsum between two sheets of paper, compressing and subsequently drying it. According to the Gypsum Association (2004), 24 different types of gypsum wallboard are available in North America ranging from 2.4 to 4.3 meters in length and with thicknesses between 6.35 mm to 25.4 mm. Traditionally, mined gypsum has been the primary source of production material.

During the manufacturing process, different chemical additives are used. For example, adhesives are used in the paper edging (Certain Teed, 2011a), anti-fungal agents are used in wallboard that may be exposed to high moisture, and glass fibers are incorporated in fire resistant wallboard for boilers or connecting walls (Certain Teed, 2011b). The primary regulatory concern is associated with post-consumer chemicals related to wall coverings, such as paints and wallpaper, which may contain heavy metals and organic contaminants.

Many wallboard manufacturers are now using FGD as the main source of raw material for their products. Increased attention to industrial gas emissions has led regulatory authorities to legislate users of fossils fuels (primarily coal fired power plants) to reduce their gaseous emissions, specifically sulphur dioxide (SO_2). A commonly employed technology is to use a counter-current flow of misted limewater into the gaseous stream to scrub out the SO_2. The limewater reacts with the SO_2 to form a precipitate of calcium sulphate, known as FGD. The FGD is sequentially removed from the water for further processing. Due to the reduced temperatures required for the operation of the scrubber, some of the volatile metals contained in the gas stream may condense out into the synthetic gypsum (Kairies et al., 2006; Shock et al., 2009; Tayibi et al., 2009). In the United States, new wallboard is increasingly being manufactured with FGD (Gypsum, 2008) which could pose additional management concerns if waste wallboard is to be diverted from landfills and used as an agricultural soil amendment (Lorrimore, 2009).

It is estimated that 4.8 kg of wallboard waste is generated for every m^2 of new construction (Mandepanda et al., 2000). In 2004, the US Geological Survey reported that 3,289 million m^2 of gypsum wallboard was produced in the United States (Founie, 2006). In Northeastern United States, 1.2 Mt of WGW was generated (653,000 tonnes of new scraps and 447,000 t of demolition/renovation waste) in 2006 (Northeast Waste Management Officials Association, 2010). It was also estimated that the City of Ottawa, Canada, sends 33,600 t of WGW annually to landfills (Gratton and Beaudoin, 2010). Currently in Nova Scotia, WGW is not recycled and is disposed of in secure construction and demolition (C&D) landfills. Twenty percent of all the material (by mass) delivered to C&D sites in the Province of Nova Scotia, Canada, is WGW (Dillon Consulting Ltd., 2006). This is typically in the form of residential or business demolition, which includes WGW from new construction activities. In some cases, the high sulphur content of gypsum placed in landfills in combination with anaerobic conditions leads to the emission of hydrogen sulphide gas, which can become a health and environmental hazard (Flynn, 1998).

Gypsum has been used in agriculture as a soil conditioner to improve the soil tilth and provide calcium and sulphur for plant nutrition (Dontsova et al., 2005). Varcoe et al. (2010) measured a significant decrease in aqueous Ca, Mg, Mn and Na when gypsum was applied at 15,000 kg ha^{-1} in the Mount Lofty Ranges area of South Australia. Turley (1998) observed that adding crushed WGW to soil could reduce subsoil hardpans by loosening the clay in soils allowing increased air and water circulation. Further work by Wolkowski (2003) found that land application of crushed wallboard on alfalfa plots was effective as a commercial gypsum fertilizer. Gypsum has also been observed to aid in the reclamation of saline-sodic soils (Hanay et al., 2004, Zia et al., 2007). Limited research has been conducted on gypsum in compost systems.

Saludes et al. (2008) reported that using the paper from waste gypsum wallboard in cattle manure compost had no negative effects on the composting process. Moreover, Marvin (2000) noted that WGW could be used as a bulking agent in compost providing calcium and sulphur as micronutrients with the paper component supplying some carbon to the compost, and acting to absorb excess moisture. While these studies have used WGW in soils or composts, the focus has been on unadulterated material which has not been treated with post manufacturing coatings, such as paint.

The objective of this study was to examine the transport and bioavailability of heavy metals in compost and soil when using WGW as a compost feedstock. The study examined material from both clean (scraps from construction projects) and coated wallboard. Compost treatments where placed over a layer of soil in a concrete lysimeter cell. The cells were equipped with drainage enabling the collection of water that had percolated through the compost and then through soil. All three media; compost, soil, and water, were tested for heavy metals concentration. A time factor was also incorporataed as total and bioavailable heavy metals concentrations were determined in compost and soil at the start and at the end of the study to determine if there was any change in these parameters over time. Compost, soil and leachate were tested for various other parameters such as pH, electrical conductivity, and chloride ion concentration.

3.2 MATERIALS AND METHODS

The following section outlines how the study was conducted, feedstocks that were used to prepare the compost, representative sampling (compost, soil, and leachate), analytical methods employed, and statistical methods used to evaluate the results.

3.2.1 Study Site / Location of Feedstocks

Three identical concrete lysimeter cells (Figure 3.1) located at the Bio-Environmental Engineering Centre (BEEC) in Bible Hill, Nova Scotia, Canada (Lat 45.386383, Long - 63.242005) were used for this study. The cell dimensions measured 4.47 m in length x 2.64 m in width x 1.5 m high. The cells are aligned side by side in a row separated by approximately 3 m. Each cell had a slope toward a central floor drain that was directed to double tipping buckets located in a heated sampling hut. The cells were exposed to local climatic conditions but were isolated from any groundwater influence.

Five feedstocks were used to generate compost mixtures for this study: used horse bedding, barley straw, Class B biosolids from a Sequential Batch Reactor (SBR) system, crushed WGW and crushed de-papered WGW. Large hemlock wood chips were added to improve bulk density and porosity. The horse bedding was obtained from local horse farmers and the Truro Raceway, a standard bred harness racing track located in Bible Hill, Nova Scotia, Canada. The horse bedding was a mixture of horse manure, sawdust,

Figure 3.1 Lysimeter Cell

wood shavings and hay. The barley straw was sourced from agricultural fields located at the BEEC facility. The Class B biosolids were provided by the County of Colchester Wastewater Treatment Facility located in Lower Truro, Nova Scotia, Canada. This facility receives sewage and storm drain wastes from the municipalities in central Colchester County.

Samples of domestically available gypsum wallboard (new and unused) were obtained and tested for heavy metals content. These samples were tested with and without the covering paper attached (paper was peeled then scraped off wallboard). WGW samples were obtained from Halifax C&D (both with and without paper) located in Goodwood, Nova Scotia, Canada. This facility receives C&D waste from the greater Halifax area, including WGW. The WGW was a combination of new construction scraps and material from building demolitions and /or home renovations. The WGW used for this study had all foreign objects removed and was crushed using a plate grinder. To obtain de-papered WGW, the crushed material was further processed by sizing to less than 9 cm with a trommel power screen. This process removed approximately 98% of the paper (conversation with supplier of WGW).

3.2.2 Experimental Design

The study was set up as a Randomized Complete Block Design with three compost treatments (control compost with no wallboard, compost with de-papered wallboard, and compost with papered wallboard) and three blocks. Time of year, or seasonality, was used as a blocking factor because of an insufficient number of lysimeter cells to conduct the experiment at one time. Block 1 was in late fall/winter, block two was in spring/summer, and block 3 was in fall. In this study, the compost treatments were placed in cells over a 30-cm layer of soil and any leachate was collected through the graded drainage inlet within each cell. Treatments were randomly assigned a cell at the beginning of each season (block). Compost treatments were not mixed during each season. New compost treatments and soil were used for each season and managed as a static unaerated pile. All feedstocks were collected fresh prior to mixing compost for each block but obtained from the original sources. Block effect also accounted for differences in raw materials between blocks (49 days).

The soil in this study was obtained from the BEEC site and consisted of an acid sandy loam till of the Woodville group (Webb et al., 1991). Soil from the same source was used for all experimental blocks but replaced prior to the start of the each new block.

3.2.3 Composting Process and Sampling

The compost treatments were prepared using a Supreme Enviro Processor Model 300 Pull Type (Supreme International Limited, Wetaskwin, Alberta, Canada) with a 7.9 m^3 capacity. This processor is equipped with a power take-off driven vertical augur to cut and mix materials added to the drum. It is outfitted with a weigh scale to determine the weight of material added, including water to correct moisture content. The drum has a side-discharge conveyor belt to build compost windrows once the material in the drum is completely mixed. Compost treatments were calculated on a dry weight basis using values obtained from analysis of the feedstocks. The compost treatments were established to achieve a carbon to nitrogen ratio (C:N) of 26: 1 to 28:1 and a moisture content of 65% (water was added to each treatment to bring it to the desired moisture content). The control treatment had the same ratios of biosolids, horse bedding and straw as the WGW treatments but with no WGW. The reasoning for this was that the only difference between the treatments would be the WGW addition.

The components of each treatment are presented in Table 3.1. Each compost treatment was approximately 7 m^3 in size. The average initial dry mass (n=3) was 748 kg, 1102 kg, and 1145 kg for the control treatment, P-WGW treatment, and the D-WGW treatment respectively. As the compost was placed directly on top of the soil it was difficult to get an accurate mass of the compost at the end of the run as it was hard to separate from the soil. Once discharged from the Enviro Processor, the compost was placed in each cell with the use of a front-end loader. The compost was placed on top of approximately 30 cm soil in each lysimeter cell with the highest point being the center while covering all of the soil. The pile was approximately 1.5 m at its greatest depth and covered an area of 11.8 m^2.

The WGW composts had a WGW content of 34% by mass (this addition rate gave the theoretical 28:1 C:N ratio) on a dry basis. The ratio of biosolids/straw/bedding was the same in all three treatments.

Table 3.1 Compost Treatment Feedstock Ratios

Treatment	Percent by Dry Weight (%)			
	Biosolids	Straw	Bedding	WGW
Control	17	63	20	0
P - WGW	11	41	14	34
D - WGW	11	42	13	34

Once the compost treatments were placed, type K thermocouples were placed at the 60 cm, 90 cm and 120 cm depths in each compost pile to measure temperature fluctuations over the season. All temperature data were collected and stored using a Campbell Scientific (Campbell Scientific Inc., Logan, Washington, U.S.A.) CR10X data logger. Temperature measurements were taken every ten minutes. The ambient temperature was also measured and recorded at the site of the lysimeter cells.

Leachate flow was monitored in the sampling hut where double dipped valves were installed. The number of buckets tips was recorded using Campbell Scientific Labview Software. The tipping buckets were calibrated so that counted tips could be converted to flow in litres. The average calibration flow for the tipping buckets (n=20) was 0.34 L, 0.40 L and 0.38 L per tip for cells 1, 2, and 3 respectively.

Feedstock samples weighing approximately one kg were collected as they were received at the research site. Six-1 kg samples were randomly collected from each compost treatment at time of preparation, bi-weekly and at the end of the experimental run, seven weeks later. Bi-weekly compost samples were collected at a depth of at least 30 cm in each pile at six random locations. Samples at the end of experimental run were collected from the cells prior to compost removal. Samples were placed in plastic bags, tightly sealed, refrigerated at 4°C if testing was to be done immediately, or frozen if not.

Six soil cores were collected randomly from around each cell using a 30 cm deep soil sampling probe (Oakfield Apparatus Inc., Fond du Lac, WI, U.S.A.) prior to compost addition and combined. At the end of each experimental block, the soil in each cell was replaced, again re-sampled and combined. All soil samples were refrigerated at 4°C for analysis at a later date.

3.2.4 Analytical Methods

Compost samples were tested for moisture content by placing a representative subsample (approximately 50 g) in an oven at 105°C oven and dried to constant weight (Carter, 1993. All compost samples were then screened through a 12.5 mm sieve to remove oversize materials. A representative portion (approximately 10 g dry weight) of the compost sample was dried at 36°C to a constant weight. Drying at this temperature prevents the potential loss of mercury during the drying process (TMECC). Dried samples were processed in a Waring professional specialty blender (Waring Products, Torrington, CT, USA). Samples were then ground using a Retsch MM300 ball mill (Retsch GmbH & Co. KG, Haan, Germany).

A slurry, with a ratio of 1 part compost to five parts water was prepared for pH, electrical conductivity (EC), and chloride concentration analysis (TMECC, 1991). The slurry was prepared by placing the required amounts of compost and deionized water into a mason jar, covering and shaking on an Eberbach 600 reciprocating shaker (Eberbach Corporation, Ann Arbor, Michigan, U.S.A.) for 20 minutes. The sample pH and EC were measured directly in the slurry using a Fisher Scientific Accumet XL50 Dual Channel pH/Ion conductivity meter (Thermo Fisher Scientific, Waltham, MA, U.S.A.) equipped with Fisher Scientific pH and electrical conductivity probes. The chloride concentration of the filtered fluid was measured using a Fisher Scientific Accumet XL50 Dual Channel pH/Ion conductivity meter equipped with a Fisher Scientific Cl electrode model no 13-620-627. The Cl electrode was calibrated using standards of 100, 250, and

500 ppm Cl prepared by making serial dilutions of a stock 1000 ppm solution. The stock solution was prepared by dissolving 1.649 g of NaCl (Fisher Scientific) in deionized water then bringing to volume in a 1000 mL volumetric flask.

Total carbon and total nitrogen analysis was performed with a Leco CN-2000 (Leco Corporation, St. Joseph, Michigan, U.S.A.) using the manufacturer's method for plant material (Leco Corporation, 2010a). A nitric acid microwave digestion method (TMECC) was used for total metals using the ground compost samples and a CEM MARS microwave digester (CEM, Matthews, NC, U.S.A.). Bioavailable metals were extracted using the ground compost samples and a Mehlich III extraction method (Carter, 1993). Extracted samples were tested for metal concentrations using a Varian 240FS Fast Sequential Atomic Absorption Spectrometer (Agilent Technologies, Santa Clara, CA, U.S.A.) equipped with a Varian SIPS 10/20 Sample Introduction Pumps System. The atomic absorption spectrometer was equipped with a Varian VGA-77 vapour generator as per the manufacture's recommendations for mercury, selenium and arsenic analysis. The instrument was calibrated using multi-element 10 ppm and 100 ppm standards prepared by Plasma-Cal (Plasma-Cal, Baie D'Urfe, Quebec, Canada).

Feedstock materials were tested in an identical manner as compost samples except for material preparation. In the case of feedstocks the entire sample was size-reduced then milled (<2 mm) prior to analyses being performed. New gypsum wallboard was purchased at various local hardware suppliers. The new gypsum wallboard was tested as is (paper attached) and with the paper removed. The WGW samples were as received at the C&D facility. The exact ratio of new to old material was not known. Soil was taken from each treatment (10 g) for gravimetric moisture analysis at 105°C until a constant weight was obtained (Carter, 1993). Soil samples were sieved to < 2 mm and air-dried. A 20 g portion of the air-dried sample was then ground using a Retsch MM300 ball mill.

Analyses for soil total metal and bioavailable metal concentration were all performed on the ground samples. Total and bioavailable metals for soil samples were extracted and analyzed by the same methods and procedures described for the compost samples.

Leachate samples were measured directly for pH, EC, and Cl by the same methods as outlined for compost samples. Leachate samples were filtered and directly aspirated for metal analysis using a Varian 240FS Fast Sequential Atomic Absorption Spectrometer (Agilent Technologies, Santa Clara, CA, U.S.A.) equipped with a Varian SIPS 10/20 Sample Introduction Pumps System.

3.2.5 Statistical Analysis

Data were analyzed using Minitab v. 16.2.2 (Minitab Inc., 2010) for descriptive statistics and SAS/STAT v. 9.3 (SAS Institute Inc., 2010) was used to complete the analysis of variance and covariance. ANOVA using seasonality as a blocking factor was used for analysis of variance within treatments. ANCOVA (using initial values as a covariate) was used for analysis of variance between treatments. The LSMEANS test was used for mean comparisons and all significant differences were considered at the $P<0.05$ probability level. Blocking was used in the ANOVA analysis to account for seasonality. This is due to the blocks being run at different times during the year. Each season had its own unique weather pattern (especially precipitation and temperature) and blocking was used to account for different influences of varying climatic conditions. Blocking for the ANCOVA analysis was used to account for seasonality as mentioned previously and the differences in initial treatment compost heavy metal chemistry (initial treatment heavy metal concentrations were used as a co-variant). The feedstocks used to prepare compost treatments for each block were from the same source but not the same batch (each batch was sourced at the time of compost treatment preparation).

3.3 RESULTS

The following sections (feedstocks, compost, soil, and leachate) outline the results of analytical testing of samples collected during this study, as well statistical analyses of the resulting data. All reported results are average values of the three blocks.

3.3.1 Feedstocks

Results of total metal analysis for new and waste gypsum wallboard samples are given in Table 3.3. The heavy metal concentrations for all four materials were similar for all metals tested. Chromium and nickel concentration was slightly higher in the waste wallboard. The de-papered wallboards were higher in zinc compared to the whole (papered) wallboard.

The waste papered wallboard was higher in lead than the waste de-papered wallboard. Both new wallboards had similar lead concentrations as the waste papered wallboard.

Although some differences were noted between the heavy metal concentrations of the four wallboard samples, none of the differences were significant in nature. For this reason it was decided to use papered and de-papered WGW to make compost.

Table 3.3 Total Heavy Metal Analysis of Papered and De-Papered New Gypsum Wallboard, Waste Gypsum Wallboard and CCME Class A Compost Guidelines

Wallboard	Cd	Co	Cr	Cu	Pb	Ni	Zn
	----------------------------------			-(mg kg^{-1})-			------------------------------
New							
Papered	6.5	12.0	6.9	16.6	62.0	9.0	46.8
De-Papered	5.9	11.0	5.7	14.1	65.7	9.7	68.1
Waste							
Papered	4.6	16.6	10.9	19.3	60.3	21.1	24.9
De-Papered	4.3	13.6	16.1	43.2	48.7	21.2	61.0
CCME	3	34	210	400	150	62	700

Comparing the results to the CCME Class A compost guidelines, it was evident that the high concentration of cadmium could pose a potential problem for composting. This could be the limiting factor on the addition of this material to compost. The compost operator would also have to be aware of the concentration of this metal in other feedstocks to be used to manufacture the compost.

Moisture content, total carbon content, total nitrogen content, pH, and EC analyses of the feedstocks used for this study are presented in Table 3.2. Horse bedding, straw and biosolids were the major sources of carbon having a total carbon content an order of magnitude great than the two WGWs. Biosolids was the major source of total nitrogen while both WGWs had none.

Table 3.2 Analysis of Compost Feedstocks

Compost Feedstock	Moisture Content (%)	Total Carbon (%)$^{¥}$	Total Nitrogen (%)$^{¥}$	C to N Ratio	pH	EC (dS m^{-1})
Feedstocks						
Bedding	69.2	36.9	0.9	41	7.3	3.4
Straw	27.8	42.6	0.4	107	7.4	3.2
Biosolids	88.8	35.0	6.6	5.3	6.6	9.9
P-WGW†	44.8	4.5	0		6.6	2.9
D-WGW†	27.4	3.6	0		6.9	2.1

† P-WGW – papered waste gypsum wallboard, D-WGW – de-papered waste gypsum wallboard
¥ On a dry mass basis

Figures 3.1 and 3.2 outlined the results of the total heavy metal concentrations of the feedstocks used for this study. The biosolids had significantly higher concentrations of copper and zinc compared to the other compost components. The D-WGW and P-WGW had higher concentrations of cadmium than the other compost feedstocks. Lead was supplied by the biosolids and two WGWs with biosolids having the highest concentration followed by the P-WGW and the D-WGW. The horse bedding had the highest concentration of chromium.

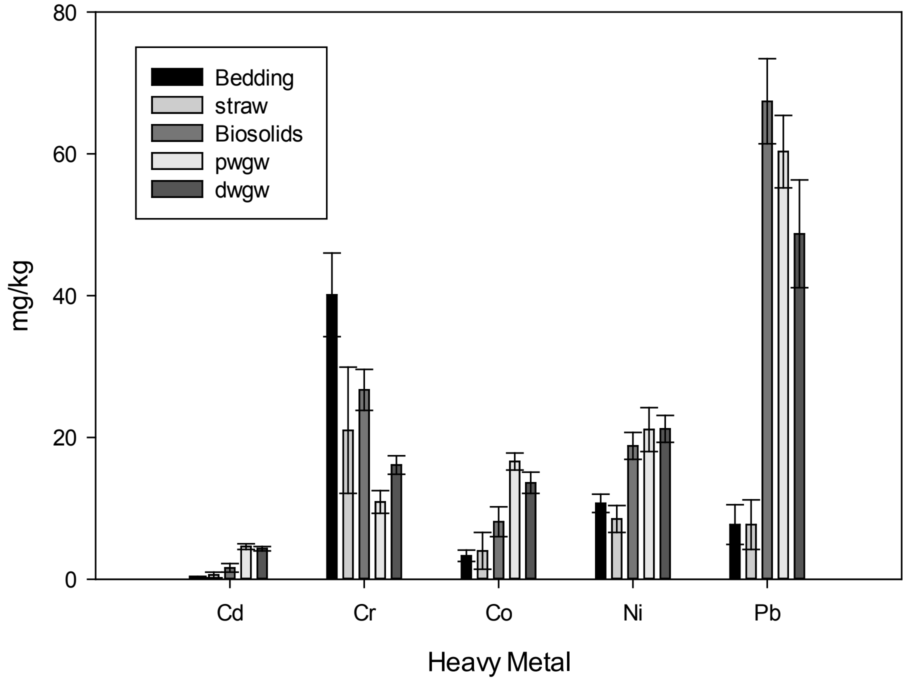

Figure 3.2 Cadmium, Chromium, Cobalt, Nickel, and Lead Total Concentration in Compost Feedstocks

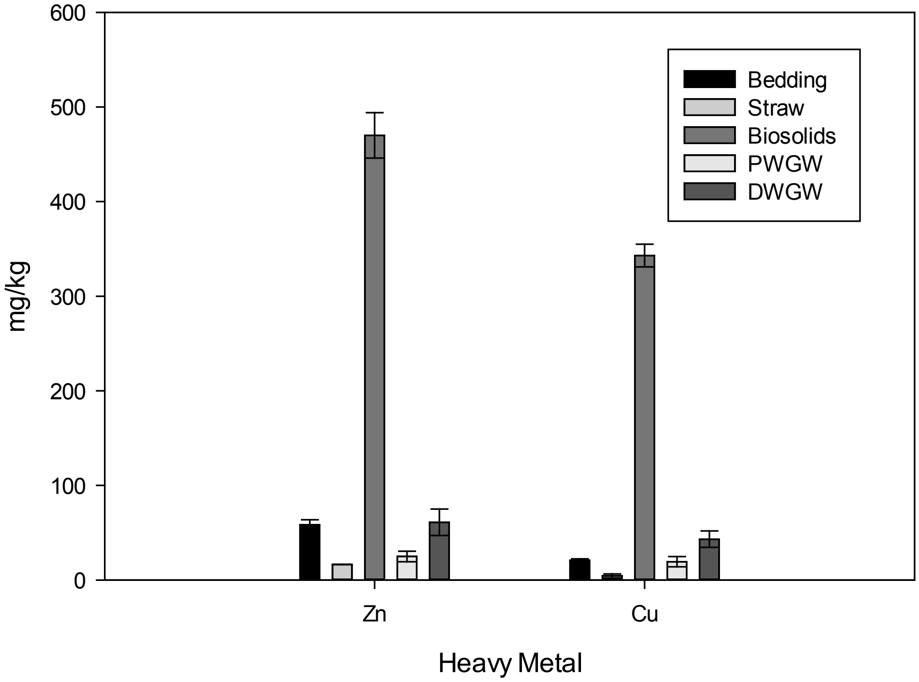

Figure 3.3 Zinc and Copper Total Concentration in Compost Feedstocks

3.3.2 Treatment Temperature Profiles

Figure 3.3 shows the three block average temperature profiles for the three treatments evaluated during the study. The papered WGW treatment produced the highest temperature in all three blocks while the control and de-papered WGW had similar temperature profiles. The P-WGW treatment reached temperatures in excess of 60°C while the other two treatments peaked out at just over 50°C. The P-WGW maintained a higher temperature than the other two treatments until approximately 40 days into the study when all three treatments returned to ambient temperatures.

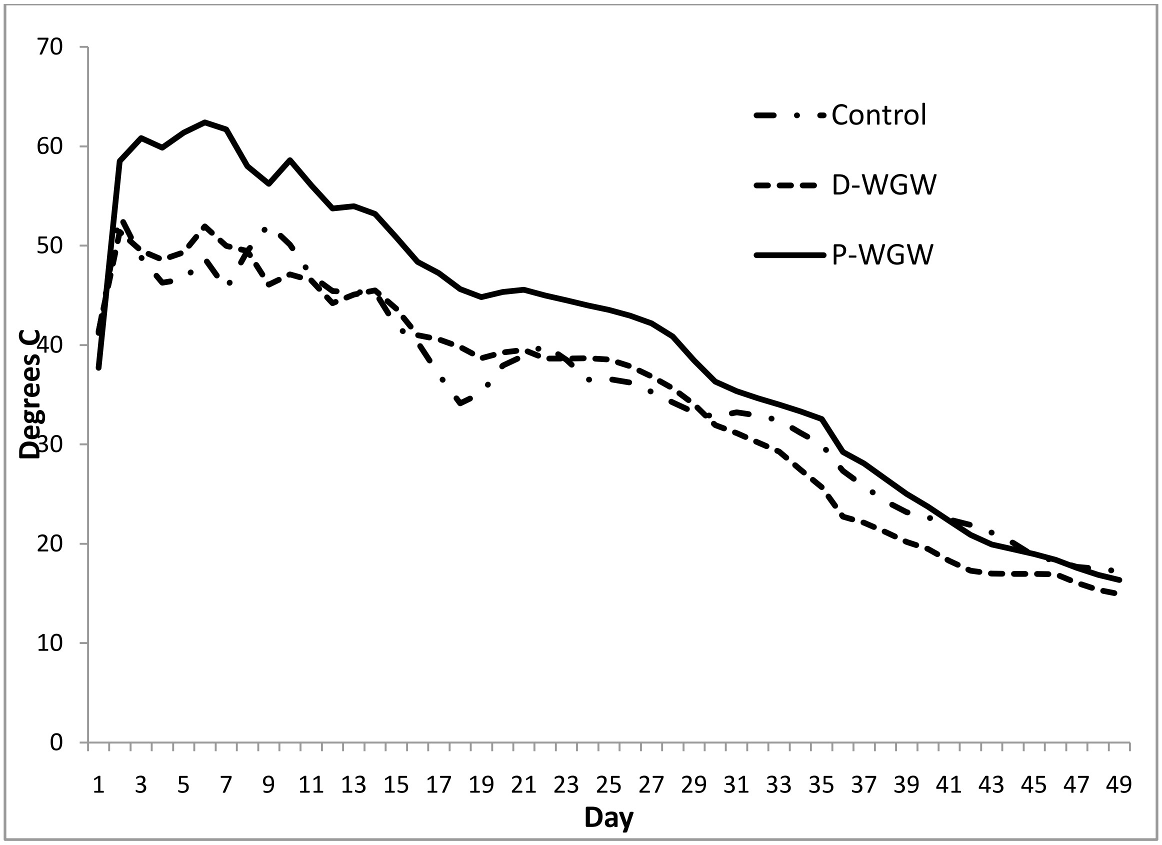

Figure 3.4 Compost Treatments Average Temperature Profiles Over the Study Period.

3.3.3 Treatment Leachate Flows

The three study seasons (blocks) experienced different environmental conditions due to the time the compost was prepared (Tables 3.4 and 3.5). Due to this timing, the rainfall during each block was quite different with block one having the highest rainfall and block two the lowest. These seasonal differences were most evident in the amount of rainfall and corresponding leachate flows through the lysimeter cells for each block. Block one had significantly higher rainfall (over five times that of block 3 and almost 14 times that of block 2) than the other two blocks. This corresponded to similar ratios for the amount of leachate from the cells.

Table 3.4 Temperature Minimum and Maximum for each Experimental Block[†]

Block	Ambient Temperature Extremes Minimum (°C)	Maximum (°C)
1	-28.3	20.6
2	-0.4	28.8
3	-10.5	23.1

[†] www.climate.weatheroffice.ca/climatedata/dailydata

Table 3.5 Total Rainfall and Leachate Flow during Each Block

Block	**Rainfall (mm)**	**Leachate Flow Through Cell (L)** **Control**	**P-WGW**	**D-WGW**
1	970	6408	6835	6220
2	284	1077	1368	1270
3	397	1395	1913	1991

3.3.4 Compost

The final compost treatment ANCOVA results are presented in Tables 3.6 and 3.7. Table 3.6. reports the P-values for the sources of error including: block, treatment, and initial (covariate) compost analyses for the various parameters of interest. Table 3.7 contains the adjusted final means from the ANCOVA for the three treatments. If only one value is presented for the three treatments final mean (in the second table) then there was no significant difference between the treatments. If there was significant difference between the treatments final mean, there will be three adjusted means presented with letter grouping.

3.3.4.1 Composting Parameters

For the compost parameters pH, electrical conductivity, chloride concentration, total carbon, total nitrogen and C:N ratio, there was no significant differences between the treatments as shown in Tables 3.6 and 3.7.

Table 3.6 ANCOVA Block, Treatment and Initial P-Values for Final Compost Parameters

Source	Compost Parameters ANCOVA P-Values					
	pH	Electrical Conductivity	Chloride	Total Carbon	Total Nitrogen	C:N Ratio
Block	0.967	0.004	0.001	0.244	0.127	0.004
Treatment	0.769	0.074	0.230	0.375	0.624	0.840
Initial	0.165	0.095	0.029	0.314	0.655	0.624

Table 3.7 Final Compost Parameters ANCOVA Adjusted Means

Treatment	Final Compost Parameters Adjusted Means					
	pH	Electrical Conductivity dS m^{-1}	Chloride mg kg^{-1}	Total Carbon %	Total Nitrogen %	C:N Ratio
Control	6.7	4.0	188	25.6	1.5	17.2
P-WGW						
D-WGW						

3.3.4.2 Total Heavy Metals

The ANCOVA of the compost treatments total heavy concentrations indicated no significant difference between the treatments (Tables 3.8 and 3.9). In this study there were no detectable amounts of arsenic, boron, selenium, or mercury in the compost samples. All compost treatments final heavy metal concentrations were below the levels set in the CCME guidelines for a Class A compost.

Table 3.8 ANCOVA Block, Treatment and Initial P-Values for Compost Total Heavy Metal Concentrations

Source	Compost Total Heavy Metals ANCOVA P-Values						
	Cd	Co	Cr	Cu	Ni	Pb	Zn
Block	0.253	0.953	0.034	0.155	0.788	0.005	0.133
Treatment	0.473	0.411	0.470	0.723	0.831	0.292	0.576
Initial	0.286	0.788	0.490	0.064	0.610	0.059	0.073

Table 3.9 Final Compost Total Heavy Metal Concentrations ANCOVA Adjusted Means and CCME Class A Compost Guidelines

Treatment	Final Compost Total Heavy Metals Adjusted Means†						
	Cd mg kg^{-1}	Co mg kg^{-1}	Cr mg kg^{-1}	Cu mg kg^{-1}	Ni mg kg^{-1}	Pb mg kg^{-1}	Zn mg kg^{-1}
Control P-WGW D-WGW	1.4	27.7	24.3	82.3	19.1	48.5	148
CCME Class A	3	34	210	400	62	150	700

† Dry weight basis

3.3.4.3 Bioavailable Heavy Metals

Significant differences were found between the compost treatments for bioavailable cadmium and zinc. Cadmium was higher in both WGW treatments compared to the control treatment following the composting period. Zinc was more bioavailable in the control treatment than the WGW treatments.

Table 3.10 ANCOVA Block, Treatment and Initial P-Values for Compost Bioavailable Heavy Metal Concentrations

Source	Bioavailable Heavy Metals in Compost ANCOVA P-Values						
	Cd	Co	Cr	Cu	Ni	Pb	Zn
Block	0.021	0.071	0.055	0.746	0.673	0.046	0.100
Treatment	0.022	0.232	0.154	0.352	0.804	0.208	0.036
Initial	0.028	0.295	0.204	0.523	0.685	0.483	0.001

Table 3.11 Final Compost Bioavailable Heavy Metals ANCOVA Adjusted Means

Treatment	Final Compost Bioavailable Heavy Metals Adjusted Means†¥						
	Cd mg kg^{-1}	Co mg kg^{-1}	Cr mg kg^{-1}	Cu mg kg^{-1}	Ni mg kg^{-1}	Pb mg kg^{-1}	Zn mg kg^{-1}
Control	0 b						120 a
P-WGW	1.6 a	1.3	0.9	17.5	1.6	11.5	96 b
D-WGW	1.3 a						95 b

† Dry weight basis

¥ Letter grouping indicates significant differences between final adjusted means between treatments

3.3.4.4 Bioavailability Fraction of Heavy Metals

The data were evaluated to determine if there was a change over time in the amount of heavy metals that were bioavailable compared to total metals. That is, what was the fraction of total metals that were bioavailable at the initial sampling compared the fraction of total metals that were bioavailable at the final sampling. This relationship, or Bioavailability Fraction (BF) (EPA, 2000), is shown graphically in Figures 3.5, 3.6, and 3.7 for the three treatments. With the exception of cadmium in the D-WGW treatment, there was no statistically significant increase in BF for any of the heavy metals over the three treatments in compost but some significant decreases were observed.

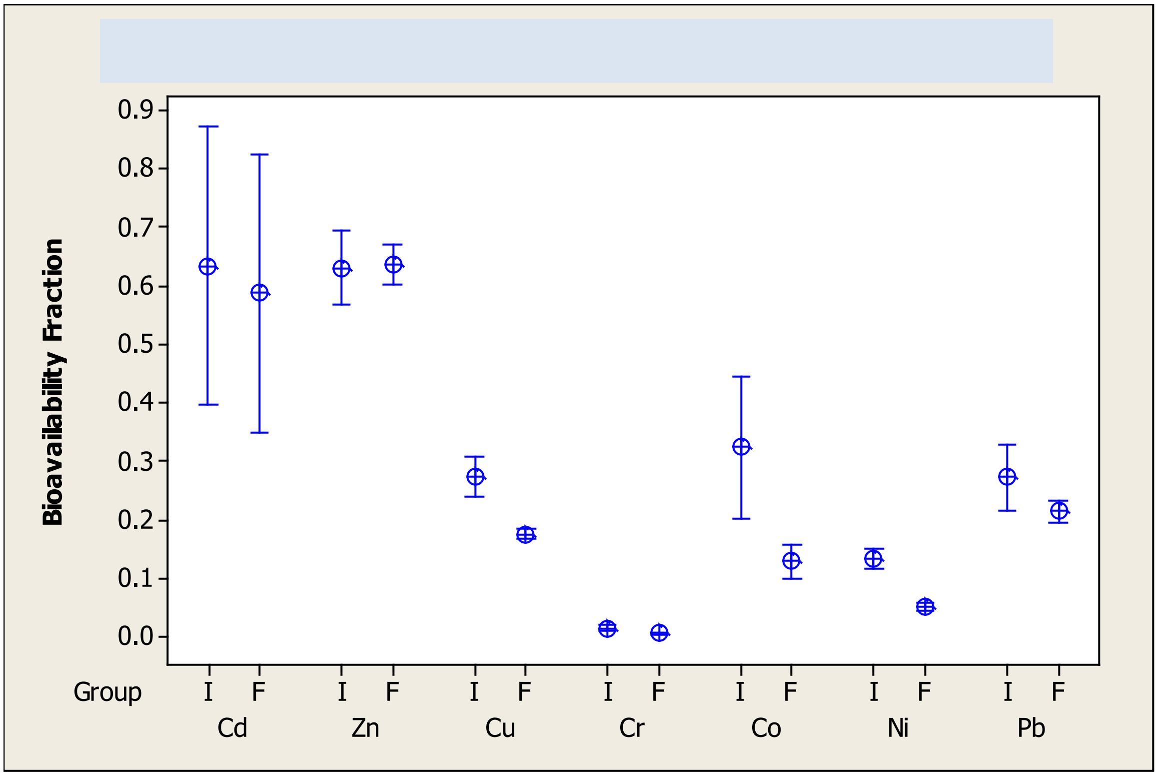

Figure 3.5 Bioavailability Factor of Heavy Metals in Compost at Initial and Final Samplings: Control Treatment

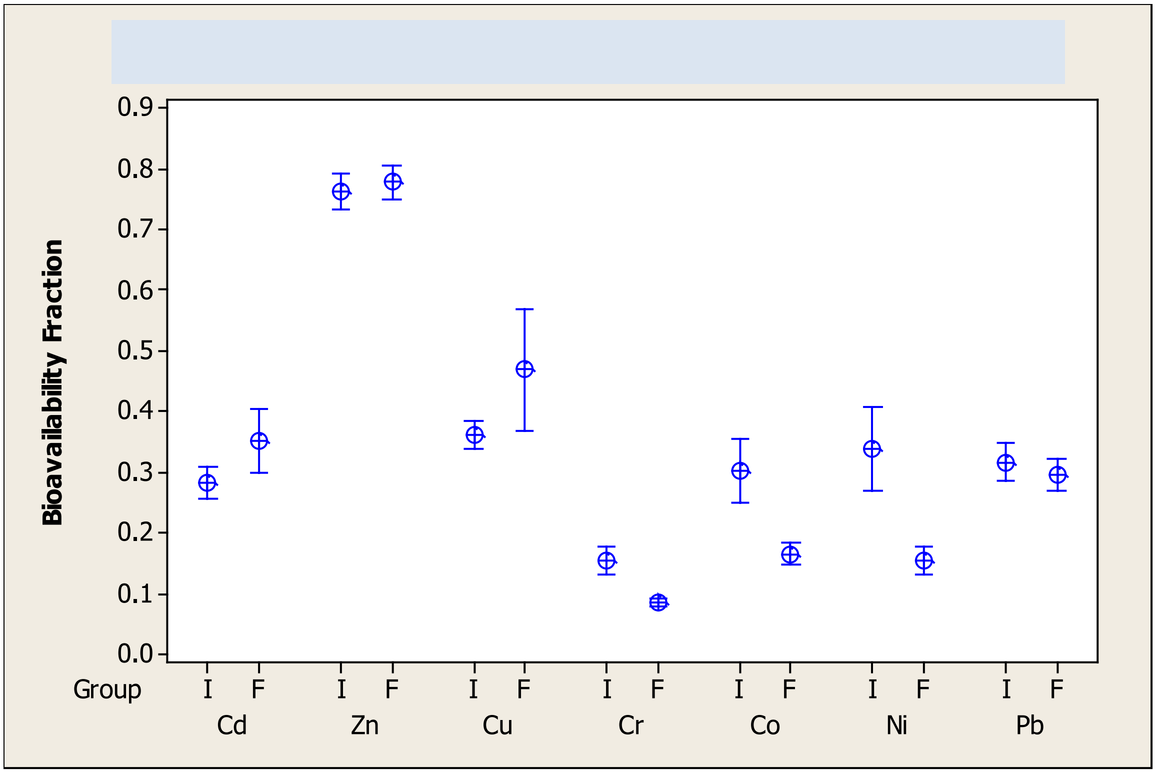

Figure 3.6 Bioavailability Factor of Heavy Metals in Compost at Initial and Final Samplings: Papered WGW Treatment

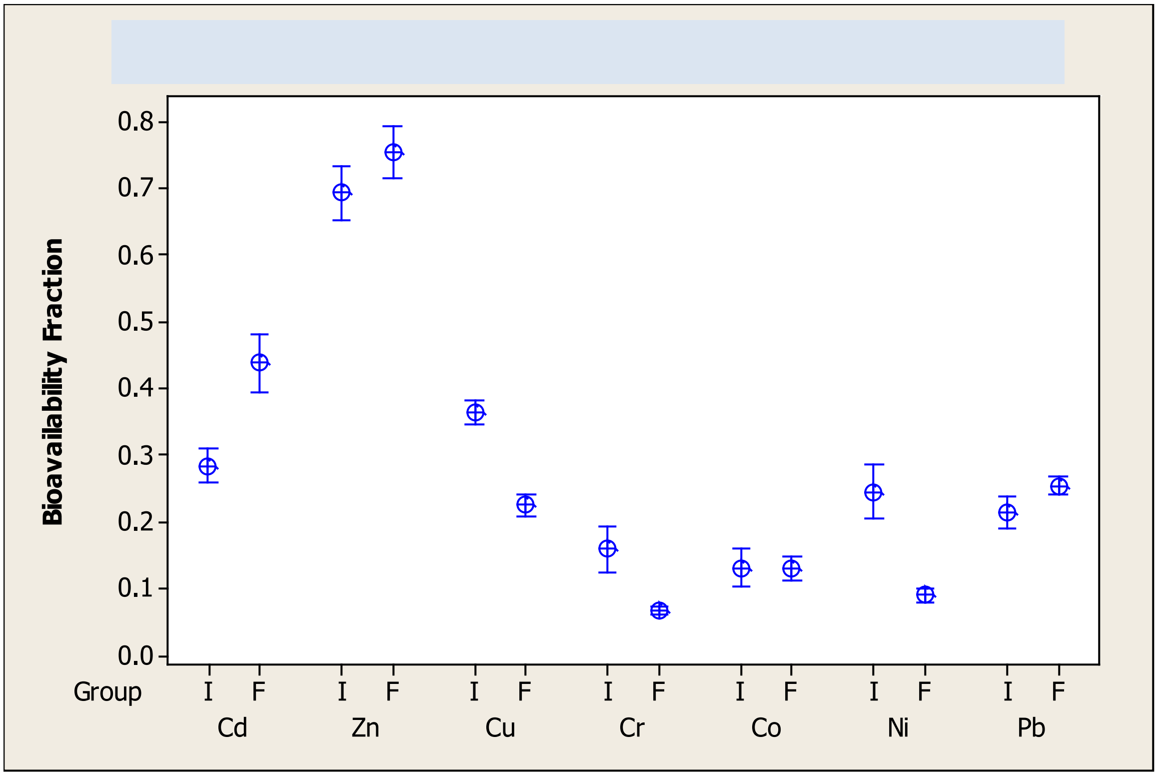

Figure 3.7 Bioavailability Factor of Heavy Metals in Compost at Initial and Final Samplings: De-papered WGW Treatment

Analysis of variance was calculated on the three treatments comparing the initial BF to the final BF (Table 3.12). For the control treatment, copper and nickel were significantly different with there being a reduction the in BF for both metals. The papered WGW treatment had a significant reduction in the BF's for chromium, cobalt, and nickel. The de-papered WGW also had a significant reduction of the BF for chromium, copper and nickel, but a significant increase in the BF for cadmium.

Table 3.12 Comparison of Initial and Final Heavy Metal Bioavailability Fractions by Treatment, ANOVA P-Values

Heavy Metal	Control	D-WGW	P-WGW
		ANOVA P-Values	
Cd	0.902	0.010	0.080
Zn	0.945	0.280	0.735
Cu	0.010	< 0.001	0.296
Cr	0.057	0.015	0.001
Co	0.154	0.957	0.017
Ni	< 0.001	0.001	0.000
Pb	0.334	0.158	0.600

3.3.5 Soil

Soil samples were collect at the start and end of the study. These samples were analyzed for pH, total heavy metal concentration, and bioavailable heavy metal concentration. The results are presented in the following sections.

3.3.5.1 pH

There were no significant differences between the pH values of the soils beneath the three treatments. The final pH of all three treatments had a highly acidic value of 4.27 (adjusted mean).This would indicate that the leachate from all three treatments had no effect on the soil pH.

Table 3.13 Soil pH ANCOVA Block, Treatment and Initial P-Values

Source	Soil pH ANCOVA P-Values
	pH
Block	0.175
Treatment	0.233
Initial	0.494

Table 3.14 Soil pH ANCOVA Adjusted Means

Treatment	Compost Response Variables Adjusted Means
	pH
Control P-WGW D-WGW	4.27

3.3.5.2 Total Heavy Metals

There were no significant differences between the final heavy metals concentrations of the soils beneath the three treatments.

Table 3.15 ANCOVA Block, Treatment and Initial P-Values for Soil Total Heavy Metal Concentrations

Source	Soil Total Heavy Metals ANCOVA P-Values						
	Cd	Co	Cr	Cu	Ni	Pb	Zn
Block	0.799	0.131	0.298	0.069	0.177	0.953	0.047
Treatment	0.573	0.693	0.282	0.590	0.460	0.411	0.346
Initial	0.790	0.383	0.256	0.330	0.196	0.788	0.100

Table 3.16 Soil Total Heavy Metals ANCOVA Adjusted Means

Treatment	Soil Total Heavy Metal Concentration Adjusted Means†						
	Cd mg kg^{-1}	Co mg kg^{-1}	Cr mg kg^{-1}	Cu mg kg^{-1}	Ni mg kg^{-1}	Pb mg kg^{-1}	Zn mg kg^{-1}
Control P-WGW D-WGW	0.8	31.2	15.5	31.2	25.7	27.7	51.9

† Dry weight basis

3.3.5.3 Bioavailable Metals

There was significant difference between the treatments for bioavailable heavy metal concentrations except for cobalt. The concentration of bioavailable cobalt was higher in the control and P-WGW treatments than in the D-WGW treatment.

Table 3.17 Soil Bioavailable Heavy Metals ANCOVA Block, Treatment and Initial P-Values

Source	Soil Bioavailable Heavy Metals ANCOVA P-Values						
	Cd	**Co**	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
Block	0.110	0.001	0.531	0.060	0.000	0.024	0.126
Treatment	0.661	0.045	0.790	0.641	0.468	0.081	0.091
Initial	0.498	0.784	0.897	0.507	0.104	0.783	0.069

Table 3.18 Soil Bioavailable Heavy Metals ANCOVA Adjusted Means

Treatment	Soil Bioavailable Heavy Metals Adjusted Means†¥						
	Cd mg kg^{-1}	**Co** mg kg^{-1}	**Cr** mg kg^{-1}	**Cu** mg kg^{-1}	**Ni** mg kg^{-1}	**Pb** mg kg^{-1}	**Zn** mg kg^{-1}
Control	0.7	1.7 a	5.1	10.5	4.5	0.2	1.4
P-WGW		1.9 a					
D-WGW		1.4 b					

† Dry weight basis

¥ Letter grouping indicates significant differences between final adjusted means between treatments

3.3.6 Leachate

Leachate samples were collected (two per day) using automated samplers installed on the drain lines of each cell. Composite daily samples were prepared and stored until required for analysis. The results are presented in the following sections.

3.3.6.1 pH

Leachate collected from the composting cells exhibited a similar pH for all three treatments during the study (Figure 3.8). The leachate collected from the WGW treatments started slightly alkaline then progressed to slightly acidic by the end of the study. The control treatment, leachate started slightly acidic, progressed to slightly alkaline and then back to acidic.

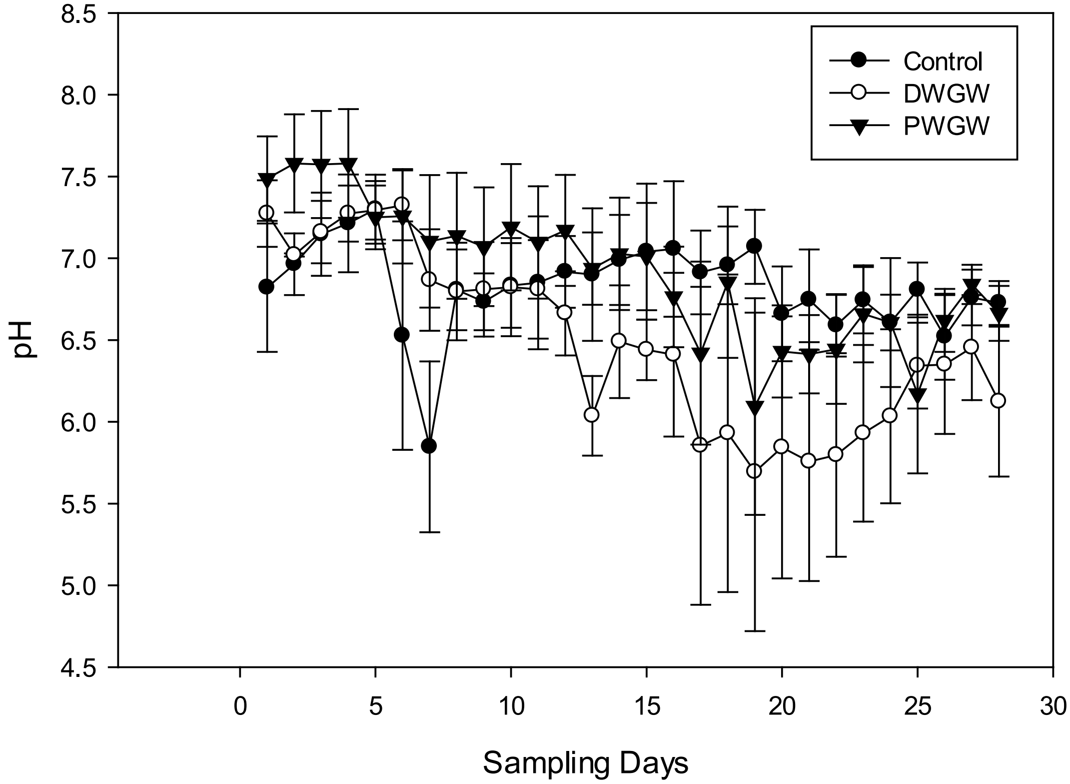

Figure 3.8 Leachate pH at Periodic Sampling Days

3.3.6.2 Electrical Conductivity

The variability of the electrical conductivity for all three treatments was very high (Figure 3.9). Initially the control and de-papered WGW treatments had higher EC than the papered WGW treatment. As the study progressed, the control treatment's leachate had a fairly consistent EC, while the P-WGW treatment EC concentration increased and the D-WGW treatment EC concentration lowered compared to the control treatment. By the end of the study all three treatments had similar EC concentrations.

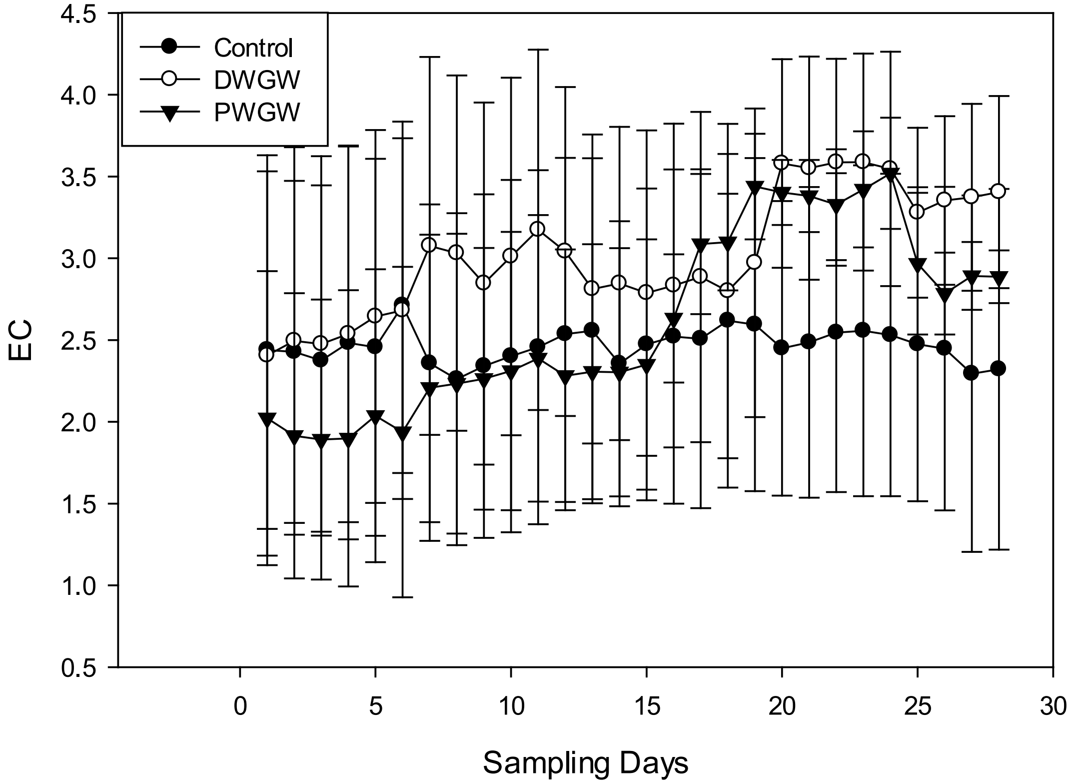

Figure 3.9 Leachate Electrical Conductivity at Periodic Sampling Days

3.3.6.3 Chloride Ion Concentration

All treatments had similar chloride concentration profiles in the leachate at the start of the study (Figure 3.10) but as the study progressed the P-WGW leachate had higher chloride ion concentrations compared to the control treatment and the D-WGW leachate had a lower chloride ion concentration. Both WGW treatments experienced a sharp decline in chloride ion concentration at the end of the study to the same level at the control treatment.

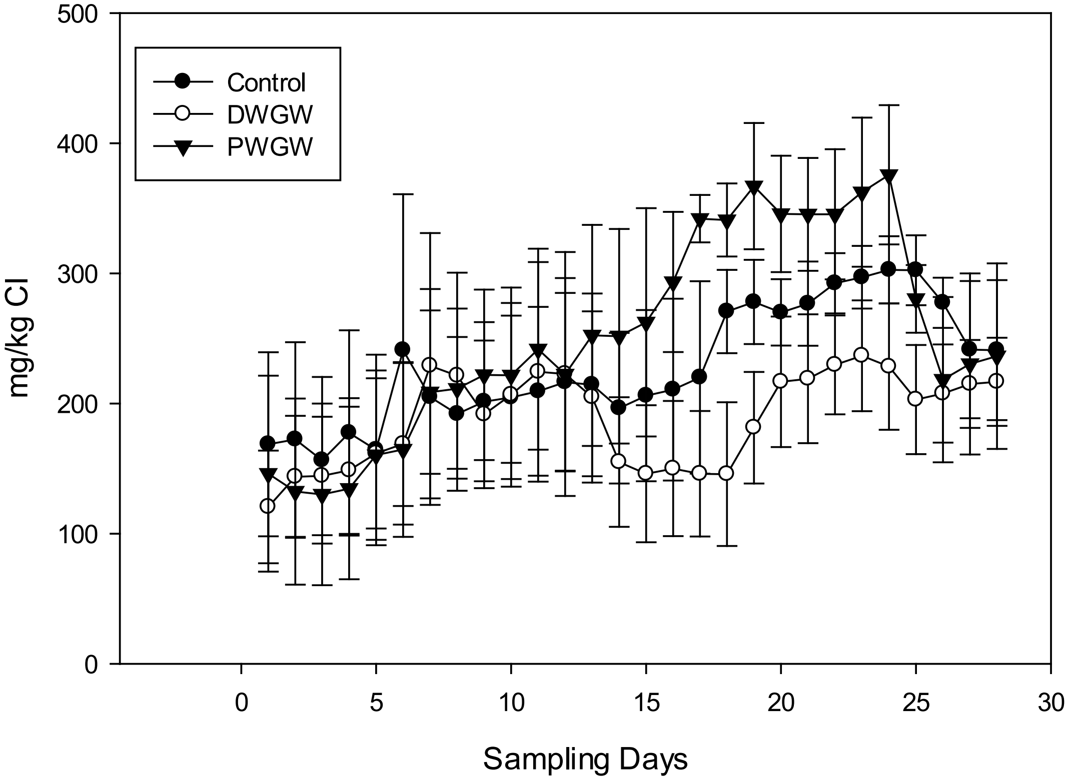

Figure 3.10 Leachate Chloride Ion Concentrations at Periodic Sampling Dayss

3.3.6.4 Soluble Metals

The leachate samples collected were analyzed for heavy metal concentration for the metals as listed in Table 3-19. The concentration for each individual sample was multiplied by the flow for that sample to generate a mass of total metal in the leachate. These amounts were then summed to arrive at a total amount of soluble metal leached out of each treatment. These values are presented in Table 3-19.

The soluble metal concentration in the leachate from all three treatments had a large variability. There was large variability associated with these data, as such, no significant differences in leachate heavy metal concentrations were detected between the three treatments.

On average, the WGW treatments had higher levels of cadmium, nickel and zinc while the control treatment had a higher copper content.

Table 3.19 Average Leachate Heavy Metal Total Mass by Treatment

Heavy Metal	Heavy Metal Mass (g)		
	Control	P-WGW	D-WGW
Cd	0.9 ± 0.9	3.9 ± 1.9	3.7 ± 0.3
Co	6.1 ± 4.8	20.1 ± 10.6	21.7 ± 6.8
Cr	15.5 ± 6.9	32.6 ± 21.3	12.0 ± 8.6
Cu	77.6 ± 65.3	41.0 ± 19.2	42.9 ± 14.0
Ni	15.1 ± 3.6	49.2 ± 20.7	47.1 ± 3.1
Pb	23.2 ± 7.6	61.8 ± 30.4	47.0 ± 17.4
Zn	88.6 ± 48.6	137.7 ± 51.3	179.6 ± 55.5

3.4 DISCUSSION

The following section will discuss in detail the findings from this study with references to other similar studies and their findings.

3.4.1 Temperature

Comparing the three treatments, the P-WGW treatment maintained higher temperatures for a longer period than the other treatments. According to the CCME Composting Guidelines (CCME 2005) composts much reach 55°C or greater for a minimum period (3 days for in-vessel or aerated static piles or 15 days for windrows) to reduce the pathogens in compost that may pose a threat to human health. Only the P-WGW maintained a temperature for greater than 55°C for a significant period of time and even then less than the required 15 days (approximately 10).

Both of the other treatments, control and D-WGW did not achieve the required temperature. All treatments did however experience a spike in temperature then a gradual decline as would be expected in a compost pile.

3.4.2 Compost Parameters

All three treatments recorded similar results for pH and there did not appear to be any influence on the soil pH as it did not change in any of the treatments. The pH of the soil will have a large effect on the movement and availability of metals (Smith 1999, Businelli et al., 1999). The soil in this study was very acidic (4.27). The pH of leachate samples tended to decline from slightly alkaline to neutral. Chen et al. (2010) reported that low molecular organic acids were transported with the leachate which may have been a factor in lowering of the leachate pH over time as the compost substrates decomposed.

There were no significant differences between the three treatments for EC in compost. As EC is an indicator of salts in solution (Chen et al., 2010, Hargreaves et al., 2008), it would be expected that as the compost treatments were exposed to more rainfall or time, that more salts would be removed from the compost and therefore higher salt concentrations would result in the leachate. In all treatment leachate, a gradual increase in EC over the length of the experiment was observed. This was evident in the ANCOVA analysis results as the block P-values were highly significant for EC, indicating that seasonal conditions had a large influence on these compost parameters.

Chloride ion concentration of the treatment leachate also indicated a removal of chloride ion from the compost treatments over time. The WGW composts, especially the P-WGW treatment's leachate, had higher chloride ion concentrations in the leachate compared to the control treatment. Chloride ion, with its high solubility in water, increased rapidly in the leachate. ANCOVA analysis of the compost samples indicated however that all three compost treatments reacted similarly with respect to chloride ion concentration from the start to the end of the study.

A reduction in the carbon to nitrogen ratio is a good indicator of the degree of degradation of compost (Greenway and Song, 2002). All three treatments in this study had similar C:N ratio change during the course of the experiment. The degradation of complex organic compounds has a strong effect on the availability of heavy metals due to their binding with organic matter (Farrell and Jones, 2010, Businelli et al., 2009). Composting variables such as pH, moisture content, temperature, and C:N ratios have a large effect on composting performance (Liang et al., 2003, Khan et al., 2009, Das and Kirkland, 2008). In this study there was no significant difference in these parameters between treatments.

3.4.3 Total Heavy Metals

No significant differences were found between the treatments in their final concentrations of the total heavy metals. In all three compost treatments, total heavy metal concentrations were below the CCME guidelines for Class A compost. This is an important measure because composts meeting this guideline have unrestricted use. There was also no significant increase in total heavy metal concentration in the soil under the compost treatments indicating that there was no transfer of heavy metals from compost to soil implying that there was no significant heavy metal leaching into the soil.

3.4.4 Bioavailable Heavy Metals

Total heavy metal concentrations are used for regulatory purposes but do not give the complete picture of availability to plants and other organisms. Warman et al. (1995) found that there was not always a good correlation between the total heavy metal concentration in the growing media and heavy metal uptake by plants. Eneji et al. (2003) found that aerobic composting increased the level of humic acid. Humic acids can then lead to increased complexation of metal ions (Paré et al.,1999) therefore reducing their availability to plants.

A number of factors can influence the binding and mobility of metals in compost and soils including pH, temperature, moisture and organic matter content. Organic matter can bind zinc, copper, chromium and cobalt thereby making them unavailable and less prone to movement (Kumpiene et al., 2008; Smith, 2009; Tisdale et al., 1993). Cadmim, zinc, copper, lead, and nickel are made less available at increasing pH (Kumpiene et al., 2008; Smith, 2009; Tisdale et al., 1993) while chromium becomes more available as it is oxidized from Cr (III) to Cr (VI) (Kumpiene et al., 2008).

The study found that there was an increase in the concentration of bioavailable cadmium in the two WGW compost treatments over the length of the study. This increase in bioavailable cadmium was not found in the soil but was evident in the cadmium total mass in the leachate from the WGW treatments. There was an average of 0.9 g of soluble cadmium in the control treatment leachate while the P-WGW treatment leachate had an average mass of 3.9 g of soluble cadmium and the D-WGW treatment leachate had an average mass of 3.7 g of soluble cadmium. This difference in cadmium bioavailability could be attributed to the presence of sulphur in the

WGW treatments. Vink et al (2010) found that the addition of gypsum to soil increased the release of cadmium from the solids phase.

The control treatment had a higher concentration of bioavailable zinc compared to the two WGW treatments. This increase in zinc bioavailability in the control treatment was not found as an increase in soluble zinc in the leachate samples collected from the control treatment compared to the two WGW treatments. Zinc is labile and therefore tends to be primarily found in the bioavailable form (Smith, 2009, Greenway and Song, 2002). The control treatment had a higher total zinc concentration and therefore it would follow that the bioavailable concentration of zinc would be higher as well.

3.4.5 Bioavailability Fraction

Greenway and Song (2002) found a slight decrease in availability of cadmium over time in composts, theorizing that the composting process leads to a change from labile to fixed form. Work has been done by the EPA (EPA, 2010) to develop a quick indicator to quantify the change in lability of heavy metals. From this work the BF was developed when an increase in BF indicates that the heavy metal in question has become more bioavailable than at a previous time. In this study, there was a significant difference in the D-WGW treatment with an increase in the BF from initial to final sampling, while the control and P-WGW treatments saw no change in the BF of cadmium from initial to final sampling. This may also have been influenced by the higher total concentration of cadmium in the D-WGW compost (1.3 mg kg^{-1}) compared to the control treatment (0 mg kg^{-1}). The P-WGW had the highest bioavailable concentration of cadmium (1.6 mg kg^{-1}) but was not significantly different at the 0.05 probability level but was significant at the 0.10 probability level. There was no significant change in compost heavy metal BF with lead in all three treatments from initial to final sampling. Chromium BF was reduced in both WGW composts but not the control compost. Greenway and Song (2002) measured a reduction from 1-3% of the bioavailable fraction to less than 0.1% over time in the composting period. Farrell and Jones (2009) measured a significant shift in the copper fractions of compost and proposed that it was likely due to changes from loosely organically bound metals to tightly organically bound forms. All three treatments saw a significant BF reduction from the initial to final sampling for copper. There was a reduction in the nickel BF for all three treatments from the initial to final compost. This is in contrast to Greenway and Song (2002) who found that nickel bioavailable fraction to be relatively stable. Smith (2009) noted that pH has an effect on nickel availability where a lower soil pH potentially increases availability. In this study the pH of all compost treatments were reduced from a slightly alkaline pH (6.9 to 7.6) initially to slightly acidic pH (6.5 to 6.7) in the final compost.

3.5 CONCLUSION

The D-WGW was found to have a similar temperature profile as the control treatment while P-WGW achieved higher temperatures than the other two treatments. Papered WGW was found to have a higher lead concentration than de-papered WGW. However, this was not evident in the final compost lead concentration with a WGW addition rate of 34%. Waste gypsum wallboard was not found to have a significantly different effect on total heavy metal concentrations compared to the control treatment. All treatments met the CCME Class A guidelines for heavy metal concentrations. Waste gypsum wallboard compost in this study was found to have a higher concentration of bioavailable cadmium even though there was no significant difference between the total concentrations of cadmium in all treatments.

While this study evaluated the potential movement of heavy metals in compost, the compost piles were static and unaerated. The next year-long study used covered compost piles, to reduce the effect of climatic conditions, to get a better understanding of the effect of WGW addition on the composting process. As little difference was found between the results for P-WGW and D-WGW, the next study used only P-WGW as a feedstock in the compost.

CHAPTER 4 COVERED COMPOST STUDY

4.1 INTRODUCTION

Wallboard is one of the most widely used interior wall construction materials in North America (Gratton and Beaudoin, 2010). Typically, wallboard is sold with a white facing paper allowing for ease of finishing and painting (Certain Teed, 2011a). Wallboard is manufactured by injecting a slurry of calcined gypsum between two sheets of paper, compressing and subsequently drying it. According to the Gypsum Association (2004), twenty four different types of gypsum wallboard are available in North America ranging from 2.4 to 4.3 meters in length and with thicknesses between 6.35 mm to 25.4 mm. Traditionally, mined gypsum has been the primary source of production material.

During the manufacturing process, different chemical additives are used. For example, adhesives are used in the paper edging (Certain Teed, 2011a), anti-fungal agents are used in wallboard that may be exposed to high moisture, and glass fibers are incorporated in fire-resistant wallboard for boilers or connecting walls (Certain Teed, 2011b). The primary regulatory concern is associated with post-consumer chemicals related to wall coverings, such as paints and wallpaper, which may contain heavy metals and organic contaminants.

It is estimated that 4.8 kg of wallboard waste is generated for every m^2 of new construction (Mandepanda et al., 2000). In 2004, the US Geological Survey reported that 3,289 million m^2 of gypsum wallboard was produced in the United States (Founie, 2006). In Northeastern United States, 1.2 Mt of WGW was generated (653,000 t of new scraps and 447,000 t of demolition/renovation waste) in 2006 (Northeast Waste Management Officials Association, 2010). It was also estimated that the City of Ottawa, Canada, sends 33,600 t of WGW annually to landfills (Gratton and Beaudoin, 2010). Currently in Nova Scotia, WGW is not recycled and is disposed of in secure C&D landfills. Twenty percent of all the material (by mass) delivered to C&D sites in the Province of Nova Scotia, Canada, is waste gypsum wallboard (WGW) (Dillon, 2006). This is typically in the form of residential or business demolition, which includes WGW from new construction activities. In some cases, the high sulphur content of gypsum placed in landfills in combination with anaerobic conditions leads to the emission of hydrogen sulphide gas, which can become a health and environmental hazard (Flynn, 1998).

The paper component of wallboard would be a good carbon source for the production of compost. As the vast majority of lignin is removed during the pulping process, the cellulose will decompose rapidly. The gypsum component of wallboard would be a good source of calcium and sulphur. Calcium and sulphur are both required for health plant production. Calcium, a macronutrient, is a component of cell walls where it is an enzyme cofactor involved in cellular membrane permeability. With a deficiency of calcium, cell membranes can fail to prevent the entrance or exit of fluids. Sulphur is another macronutrient that is a component if amino acids, proteins, and enzyme activities.

There has been little documented work on the composting of wallboard. Arnold (2010) performed a study on the composting of clean (unused) wallboard with municipal wastes. This study found that the compost produced was of acceptable quality although there were concerns with the level of some heavy metals, including vanadium, as well as boron. Saludes et al. (2008) conducted a study using the paper from wallboard to produce compost using cattle manure. This study found increased calcium content in the compost but no phyto-inhibitory effects. Both of these studies used clean gypsum wallboard. There has been little work done on the impacts of using waste gypsum wallboard as a compost additive.

This study examined compost made with a mixture of gypsum wallboard (from clean scraps from construction projects) and from painted sources as received at the C&D facility), hay, and used horse bedding. Another compost was prepared using hay and used horse bedding to act as a control. The prepared composts were stored in covered bins and managed by periodic turning and moisture content adjustment if required. The compost was sampled at the beginning of the study, at each turning, and at the end of the study to evaluate the compost for various parameters.

The objective of this study was to examine the impact on the composting process when using WGW as a compost feedstock. Of prime interest in this study was to determine the effect, if any, WGW would have on compost degradation and quality.

4.2 MATERIALS AND METHODS

The following section outlines how the study was conducted, describes feedstocks used to prepare the compost, explains the compost sampling protocol, the analytical methods employed, and the statistical methods used to evaluate the results.

4.2.1 Study Site / Location of Feedstocks

A covered composting facility consisting of eight side-by-side wooden sided bins located at the Bio-Environmental Engineering Centre (BEEC) in Bible Hill, Nova Scotia, Canada (Lat 45.386383, Long -63.242005) were used for this study. The bin dimensions measured 3.66 m long x 2.18 m in wide x 1.63 m high (Figure 4.1). The bins are walled on three sides to a height of 1.63 m (open above this height), covered with a roof, and open on the north side to allow for equipment access. The bins have a concrete floor that is gently sloped to a rear drain to allow the run-off of leachate. The leachate is then directed to a collection pit were it can be collected for the individual bins.

Figure 4.1 Example of Covered Compost Bin Used in the Study.

Three feedstocks were used to generate compost mixtures for this study: horse bedding, timothy hay, and a crushed mixture in unknown proportions of new and used WGW (paper still attached). The horse bedding was obtained from the Truro Raceway, a standard bred harness racing track located in Bible Hill, Nova Scotia, Canada. The horse bedding was a mixture of horse manure, sawdust, wood shavings and hay. The timothy hay was sourced from a local beef farm. The waste gypsum wallboard (WGW) was obtained from Halifax C&D Recycling Ltd. located in Goodwood, Nova Scotia, Canada. This facility receives construction and demolition (C&D) waste from the greater Halifax area, including WGW. The WGW was a combination of new construction scraps and material from building demolitions and /or home renovations. The WGW used for this study was crushed using a plate grinder, screened to < 9 cm and all foreign objects were removed. Another screen sized at < 1.9 cm was employed for further size reduction.

4.2.2 Experimental Design

The experimental design for this study consisted of two treatments (control with no WGW and WGW at one level) with four replications in a Completely Randomized Design. The compost treatments were assigned to a bin on a randomized basis. Sufficient quantities of feedstock were sourced to produce all compost mixtures from the same batch. All compost treatments were individually produced (a subdivided batch process was not used) prior to placement into the appropriate bin. All initial compost treatment mixtures were produced within seven days. All compost treatment re-mixes were completed with three days.

The WGW compost treatment was designed to have a carbon to nitrogen ratio (C:N) of approximately 32:1 and a moisture content of 52 percent. The control treatment was prepared with the same ratios of hay and horse bedding as the WGW treatment (this would yield a higher C:N ratio than 32.:1). As with the previous lysimeter study, this experiment was done to study the effect of the WGW addition to the compost mixture. The compost mixtures were prepared on a wet weight basis. A WGW addition rate of 18% on a dry basis was used for the WGW treatment. Water was added to each mixture to achieve the desired moisture content. The compost treatments were periodically sampled and checked for moisture content. If the moisture content was 10% below the design moisture of 52%, the treatment was re-mixed with the addition of water to bring the compost back to target moisture content. Once thoroughly mixed, the compost treatment replicates were returned to their respective bins.

4.2.3 Composting Process and Sampling

The compost treatments were processed for 353 days (Table 4.2), starting on Jun 29, 2011 and ending with the final sampling on June 19, 2012. The compost treatments were turned according to Table 4.1. The compost treatments were prepared (and re-mixed) using a Supreme Enviro Processor Model 300 Pull Type (Supreme International Limited, Wetaskwin, Alberta, Canada) with a 7.9 m^3 capacity and a built-in weigh scale.

Table 4.1 Compost Treatments' Age at Day of Turning and Sampling

	Turning / Sampling				
	1	2	3	4	5
Compost Age (Days)	0	46	123	310	353

Compost treatment recipes were all calculated on a dry weight percentage basis. The ratios of feedstocks used for each compost treatment replicate are presented in Table 4.2. Each compost treatment replicate was approximately 7 m^3 in size. The compost feedstocks were mixed on a wet basis and then placed in the composting bin. Once each compost treatment replicate was placed, type K thermocouples were placed at the 60 cm, 90 cm and 120 cm depths in the compost pile to measure temperature fluctuations over the length of the study. All temperature data were collected and stored using a Campbell Scientific (Campbell Scientific Inc., Logan, Washington, U.S.A.) CR10X data logger. Temperature measurements were taken every fifteen minutes. The ambient temperature was also measured and recorded at the site of the compost bins.

Table 4.2 Compost Treatment Feedstock Ratios (% Dry Mass)

Treatment	**Feedstock Ratio (% dry mass)**		
	Hay	**Bedding**	**WGW**
Control	**67**	**33**	**0**
WGW	**55**	**27**	**18**

Feedstock samples weighing approximately 1 kg were collected from batches as they were received at the research site prior to mixing. Six-1 kg samples were randomly collected from each compost treatment at the time of compost preparation and re-mixed. Samples were placed in plastic bags, tightly sealed, and refrigerated at 4°C if testing was to be done immediately or frozen at approximately -18°C if not.

4.2.4 Analytical Methods

Compost samples were tested for moisture content by placing a representative subsample in an oven at 105°C oven and drying to constant weight as per Carter (1993). The sample was then split into two representative samples, one for testing and the other frozen. All test samples were screened through a 12.5 mm sieve to remove oversize materials. A representative portion (approximately 10 g dry weight) of the test sample was dried at 36°C to a constant weight. Dried samples were processed using a Waring professional specialty blender (Waring Products, Torrington, CT, USA) and then ground using a Retsch MM300 ball mill (Retsch GmbH & Co. KG, Haan, Germany). The remainder of the sample was stored in tightly sealed plastic bags (at 4°C if used within two weeks or frozen if longer).

The milled compost samples were used for total carbon (C), total nitrogen (N), sulphur (S), total metals and bioavailable metals analysis. Carbon and nitrogen analysis was performed with a Leco CN-2000 (Leco Corporation, St. Joseph, Michigan, U.S.A.) using the manufacturer's method for plant material (Leco Corporation, 2010a). Sulphur analysis was performed using a Leco CNS-1000 (Leco Corporation, St. Joseph, Michigan, U.S.A.) using the manufacturer's method for plant material (Leco Corporation, 2010b). A nitric acid microwave digestion method (TMECC) was used for total metals using a CEM MARS microwave digester (CEM, Matthews, NC, U.S.A.). Bioavailable metals were extracted using a Mehlich III extraction (Carter, 1993). Extracted samples were tested for metal concentrations using a Varian 240FS Fast Sequential Atomic Absorption Spectrometer (Agilent Technologies, Santa Clara, CA, U.S.A.) equipped with a Varian SIPS 10/20 Sample Introduction Pumps System for cadmium, chromium, cobalt, copper, lead, nickel, and zinc. The atomic absorption spectrometer was equipped with a Varian VGA-77 vapour generator as per the manufacture's recommendations for mercury, selenium and arsenic analysis. The instrument was calibrated using multi-element 10 ppm and 100 ppm standards prepared by Plasma-Cal (Plasma-Cal, Baie D'Urfe, Quebec, Canada).

Compost pH, EC, and Chloride ion concentration were measured on a 1:5 compost to water slurry (TMECC, 1991). The slurry was prepared by placing the required amounts of compost and deionized water into a mason jar, covering and shaking on an Eberbach 600 reciprocating shaker (Eberbach Corporation, Ann Arbor, Michigan, U.S.A.) for 20 minutes. The sample pH and EC were measured directly in the slurry using a Fisher Scientific Accumet XL50 Dual Channel pH/Ion conductivity meter (Thermo Fisher Scientific, Waltham, MA, U.S.A.) equipped with Fisher Scientific pH and electrical conductivity probes. The chloride ion concentration of the clarified fluid was measured using a Fisher Scientific Accumet XL50 Dual Channel pH/Ion conductivity meter equipped with a Fisher Scientific Chloride ion electrode model no 13-620-627. The chloride ion electrode was calibrated using standards of 100, 250, and 500 ppm Cl^- prepared by making serial dilutions of a stock 1000 ppm solution. The stock solution was prepared by dissolving 1.649 g of NaCl (Fisher Scientific) in deionized water then bringing to volume in a 1000 mL volumetric flask. Feedstock materials were tested in an identical manner as compost samples.

Compost maturity testing was conducted using an alkali trap method as outlined by TMEEC on the final compost samples (TMECC, 2002).

4.2.5 Statistical Analysis

Data were analyzed using Minitab for descriptive statistics and SAS/STAT v. 9.3 (SAS Institute Inc., 2010) PROC GLM ANOVA for CRD employing the Tukey test for mean comparisons; significant differences were considered at the $p<0.05$ probability level.

4.3 RESULTS

The following section outlines the analytical results for the two compost treatments. All results presented in this section, unless otherwise indicated, are the average of the four replicates for both treatments. The results of the Tukey analysis are reported by two methods. Lower case letters in tables indicate significant differences between samples of the same treatment over the length of the study. Upper case letters in tables indicate significant difference between treatments at specific sampling periods.

4.3.1 Feedstocks

Hay and horse bedding provided the majority of the carbon and all of the nitrogen to the compost treatments (Table 4.3). WGW provided less than 10% of the carbon compared to the other two feedstocks. Hay had a chloride concentration of 880 mg kg $^{-1}$ that was double that of the horse bedding and more than eight times that of the WGW. All feedstocks had a similar pH and electrical conductivity.

Table 4.3 Compost Treatment Feedstock Analysis

Feedstock	Moisture Content (%)	Total Carbon (%)	Total Nitrogen (%)	C:N Ratio	pH	EC (dS m^{-1})	Cl (mg kg^{-1})
Hay	16.9±0.4	39.6±0.3	1.2±0.1	32	6.5±0.2	4.0±0.0	880±100
Horse Bedding	59.7±1.6	36.8±0.5	0.9±0.1	40	7.3±0.0	3.4±0.3	416±70
WGW	45.4±0.4	4.3±0.8	0±0		6.6±0.0	2.9±0.1	34±13

The hay used for this study was not a significant source of any of the heavy metals studied (Figure 4.2). The horse bedding had a chromium concentration almost three times that of the WGW and almost five times that of the hay. The zinc concentration in the horse bedding was double that of the WGW and over four times that in the hay. WGW had a cadmium concentration of 5.3 mg kg $^{-1}$ that was significantly higher than the hay at 0.3 mg kg $^{-1}$ and horse bedding at 0.1 mg kg $^{-1}$. The cobalt concentration in the WGW was ten times that in the horse bedding and 20 times that in the hay. The WGW in this study was the major source of lead with a concentration of 53.2 mg kg $^{-1}$ compared to 7.9 mg kg $^{-1}$ in the horse bedding and no detectable amounts in the hay.

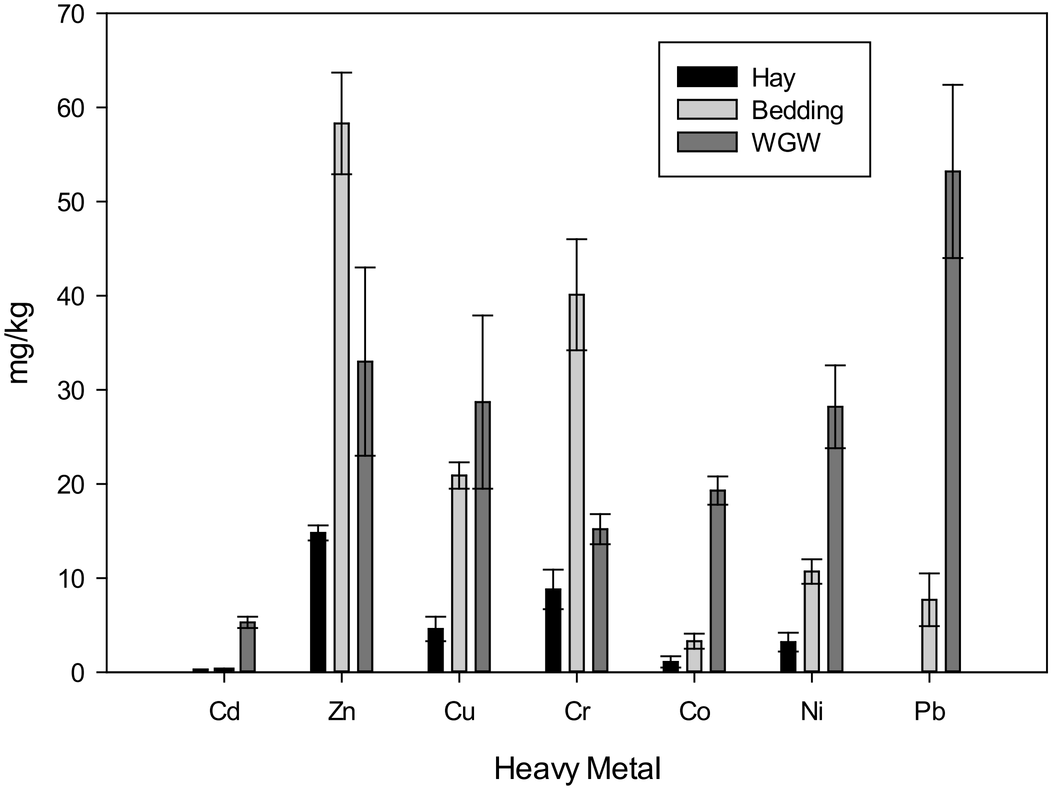

Figure 4.2 Compost Feedstock Total Heavy Metal Concentrations (n=6).

4.3.2 Compost Treatments

The dry mass and percent ratios of feedstocks in each treatment are presented in Table 4.4. The control treatment replicates averaged 67 percent hay and 33 percent horse bedding. The WGW treatment replicates had 18 percent WGW, 55 percent hay and 27 percent horse bedding on a dry basis. The two-to-one ratio of hay to horse bedding in the WGW treatment was maintained in the control treatment.

Table 4.4 Compost Treatment Feedstock Ratios

Treatment	Feedstock Ratio (% dry basis)		
	Hay	Bedding	WGW
Control	**67**	**33**	**0**
WGW	**55**	**27**	**18**

4.3.3 Treatment Temperature Profiles

The temperature data presented is an average of three temperature probes in each individual pile and an overall average of the four replicates per treatment. The control treatment compost had a more rapid initial rise in temperature to just over 60°C compared to the WGW treatment which had a slower rise in temperature to approximately 58°C (Figure 4.3). While the WGW treatment had a slower rise, once higher temperatures were reached these were maintained until the first re-mixing while the control treatment had a gradual decline. After the first compost re-mix, the control treatment temperature rose again to 65°C while the WGW treatment was hotter at 71°C. After the first re-mixing, the WGW compost experienced a rapid decline in temperature compared to the more gradual decline of the control treatment. After the second re-mix at 123 days, the control treatment temperature rose rapidly to 54°C while the WGW compost only rose to 34 °C. From this point both treatments rapidly lost temperature until they were at ambient conditions. For re-mix in the spring at 310 days, both treatments had a moderate rise in temperature with quick declines.

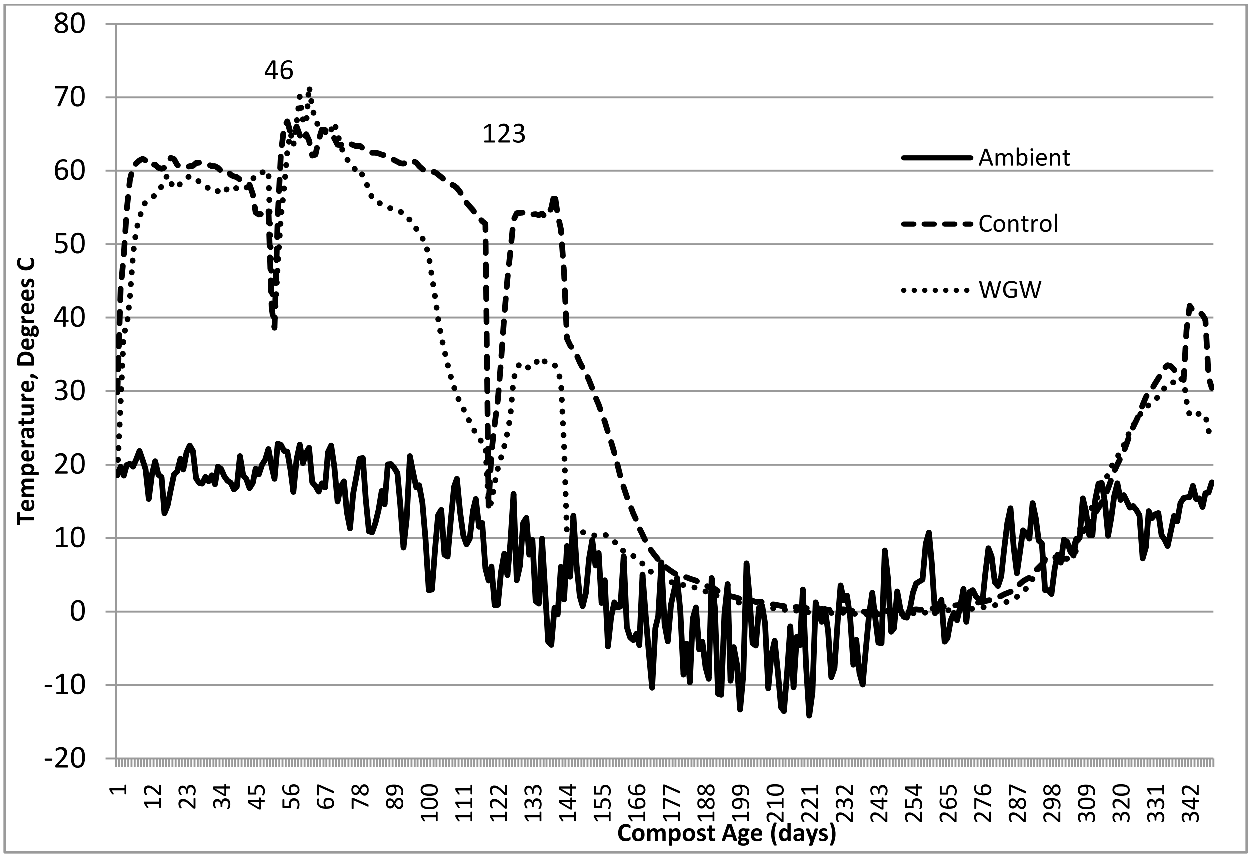

Figure 4.3 Average Compost Treatments Temperature Profile at Compost Day of Age.

4.3.4 Compost

The compost treatments experienced a steady decline in dry mass weight from the start of the study with a tapering off at the end of the experiment (Table 4.5). Converting this data do percent mass loss in Table 4.6, a distinct difference was noted between the two treatments. The control treatment percent loss was higher than the WGW treatment at all sampling periods. The percent dry mass loss for the control compost treatment was significantly higher at 49.9% compared to the WGW compost treatment at 38.3% at the last sampling of the study.

Table 4.5 Average Compost Treatments Dry Mass over Study Period

Treatment	Compost Dry Mass (kg) Day				
	0	46	123	310	353
Control	1002	866	701	538	502
WGW	1014	912	744	667	626

Table 4.6 Average Compost Treatments Percent Dry Mass Loss over Study Period

Treatment	Compost Dry Mass Loss (%) Day				
	0	46	123	310	353
Control	0	13.6	30.1	47.3	49.9
WGW	0	10.1	26.4	34.2	38.3

The was no significant difference between the moisture contents of both compost treatments (Figure 4.4) at the five sampling points although the moisture content of the treatments were significantly higher during the later part of the study compared to the first two samplings. The moisture contents of the two treatments were higher than the desired value after the second re-mixing due to an error in water addition rate. This higher moisture content was maintained until the end of the study, even though no additional water was added at the third and forth re-mixing.

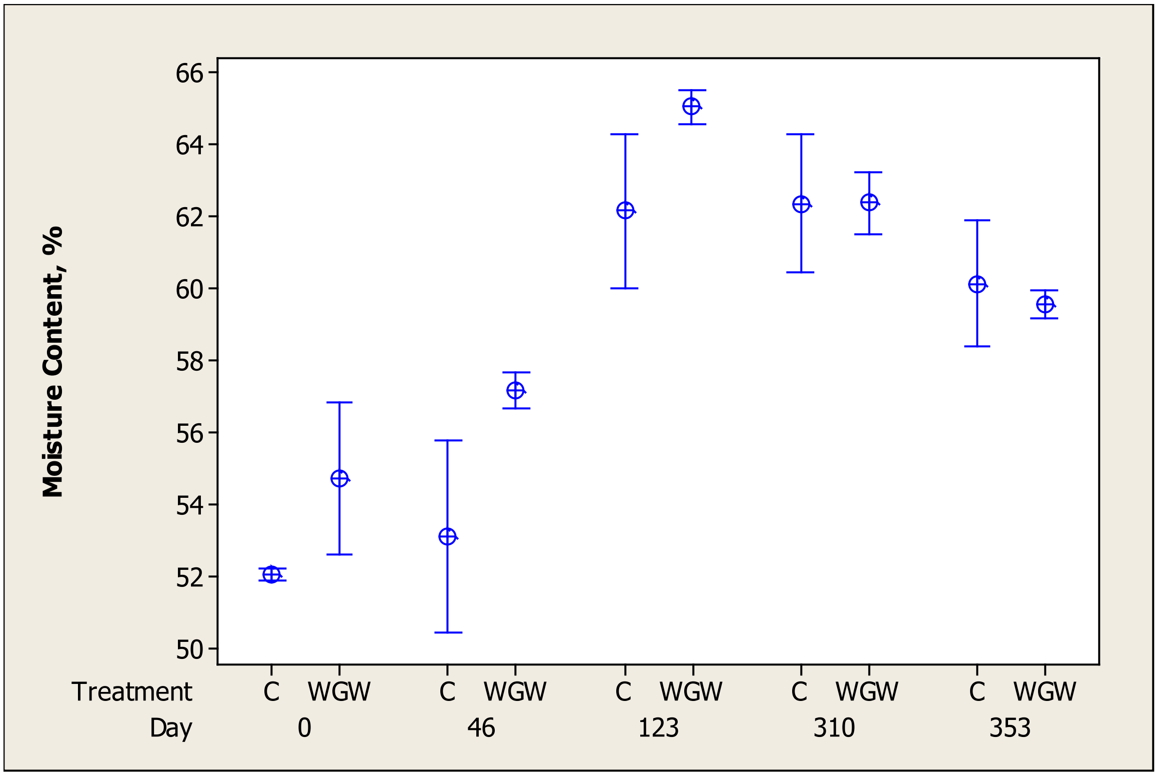

Figure 4.4 Average Compost Treatments Moisture Content at Compost Day of Age

4.3.4.1 pH

The control compost treatment had an initial pH of 6.9 which decreased to 6.2 on the second sampling then increased to 7.3 to 7.5 for the remaining samplings (Table 4.7). The final two compost samplings had a significantly higher pH than the initial sampling. The WGW compost treatment showed an increasing pH level over the study from an initial pH of 6.4 to a final pH of 7.2. While both treatments had similar pH levels at the initial sampling, the control treatment had a significantly higher pH level at the final sampling compared to the WGW treatment (7.4 compared to 7.2).

Table 4.7 Average pH in Compost Treatments (WGW vs. Control) over the Study Period.

Treatment	pH †				
	Day				
	0	46	123	310	353
Control	6.9	6.2	7.3	7.5	7.4
	a A	b B	ac A	c A	c A
WGW	6.4	6.9	7.2	7.0	7.2
	a A	ab A	b A	b B	b B

†Numbers with the same lower case letters across the row and the same upper case letters within each column are not significantly different

4.3.4.2 Electrical Conductivity

Electrical Conductivity content increased in both treatments from the first to the third sampling, both almost doubling from their initial concentrations (Table 4.8). Beyond the third sampling, there was significant difference in the control treatment EC while the WGW treatment saw a significant reduction in the EC content of the compost. The EC of the WGW treatment was significantly higher than the control treatment at all sampling points except for the final sampling when they were similar.

Table 4.8 Average Electrical Conductivity (dS m^{-1}) Content in Compost Treatments (WGW vs. Control) over the Study Period.

Treatment	Electrical Conductivity dS m^{-1} †				
	Day				
	0	46	123	310	353
Control	5.7	7.1	10.5	9.2	9.8
	a B	a B	b B	b B	b A
WGW	7.3	9.7	14.1	10.6	10.5
	a A	b A	c A	b A	b A

†Numbers with the same lower case letters across the row and the same upper case letters within each column are not significantly different

4.3.4.3 Chloride

There was no significant difference in chloride concentration in the control compost treatment between the first and second sampling, while there was a significant increase in chloride concentration between the last three samplings (Table 4.9). An increase in the chloride concentration was recorded in the WGW compost treatment between the first and second sampling which continued into the third sampling. However, this trend was reversed in the final two samplings of the WGW compost treatment where the chloride concentration was similar to the initial sampling.

Table 4.9 Average Chloride Concentration (mg kg $^{-1}$) Content in Compost Treatments (WGW vs. Control) over the Study Period.

Treatment	**Chloride Concentration mg kg $^{-1}$ †**				
	Day				
	0	46	123	310	353
Control	966	949	1661	1608	1600
	a A	a A	b A	b A	b A
WGW	887	1160	1426	1063	1032
	a A	ab A	b A	a B	a B

†Numbers with the same lower case letters across the row and the same upper case letters within each column are not significantly different

In comparing the control and WGW treatments, there was no significant difference in the chloride ion concentration in either compost treatment at the time that they were prepared. The chloride concentration in the two compost treatments was also similar at the second and third sampling. The chloride concentration in the control compost treatment was over 60% higher in the final two samplings compared to the WGW compost treatment.

4.3.4.4 Total Carbon

The control compost treatment had significantly higher total carbon content, almost 7%, compared to the WGW compost treatment when they were initially prepared (Table 4.10). This trend continued throughout the study although the difference increased to 11% by the end of the study. The control treatment, however, only had an 8.5% drop in carbon concentration from the start to the end of the study as the decrease was only from 40.1% to 36.7%. By contrast, the WGW compost treatment had a significant decrease in carbon content over the length of the study of 24%, from 33.2% to 25.2% total carbon.

Table 4.10 Average Total Carbon (%) Content in Compost Treatments (WGW vs. Control) over the Study Period.

Treatment	**Total Carbon (%)** †				
			Day		
	0	46	123	310	353
Control	40.1 a A	38.9 a A	36.8 a A	36.6 a A	36.7 a A
WGW	33.2 a B	30.0 b B	26.8 c B	26.9 c B	25.2 c B

†Numbers with the same lower case letters across the row and the same upper case letters within each column are not significantly different

However, looking at carbon reduction from a total mass of carbon point of view, in each of the two treatments (Table 4.11), this study found that even though the amount of total carbon in the WGW treatment was lower than that of the control treatment, the average total loss of carbon from the start to end of the study was similar (WGW – 53%, control – 54%).

Table 4.11 Average Total Carbon (%) Content in Compost Treatments (WGW vs. Control) over the Study Period

Treatment	Total Carbon Mass(kg)				
	Day				
	0	46	123	310	353
Control	402	337	258	197	184
WGW	337	274	199	179	158

Maturation testing was conducted on the final compost treatment samples by the carbon respiration - alkali trap method. Both composts were found to be very stable with an average carbon emission rate of 1.3 and 1.1 mg CO_2-C g^{-1}OM d^{-1} for the control and WGW treatments, respectively.

4.3.4.5 Total Nitrogen

The control compost treatment nitrogen content increased 1.8 times from 1.35% to 2.4% over the composting process (Table 4.12). The WGW compost treatment nitrogen content increased significantly as well but to a lower extent at 1.4 times. The nitrogen content was significantly lower in the WGW treatment compared to the control treatment for the length of the study. Both treatments recorded an increase in nitrogen content from the initial sampling to the third sampling after which the nitrogen contents were similar. Calculating the total nitrogen differences on a mass basis, there was a net loss of nitrogen from both composts. The loss was 10.9% from the control compost and 14.9% from the WGW compost.

Table 4.12 Average Total Nitrogen (%) Content in Compost Treatments (WGW vs. Control) over the Study Period.

Treatment	Total Nitrogen (%) †				
	Day				
	0	46	123	310	353
Control	1.35	1.62	1.98	2.31	2.40
	a A	ab A	bc A	c A	c A
WGW	1.11	1.34	1.57	1.61	1.53
	a B	b B	c B	c B	c B

†Numbers with the same lower case letters across the row and the same upper case letters within each column are not significantly different

The carbon nitrogen ratios of both compost treatments averaged 30:1 at initial mixing and dropped over the length of the study. At all five sampling periods there was no significant difference between the C:N ratios of the two compost treatments (see Figure 4.5). Both compost treatments has a similar reduction in the C:N ratios over the length of the study with a 51% and 55% reduction for the control treatment and the WGW treatment respectively.

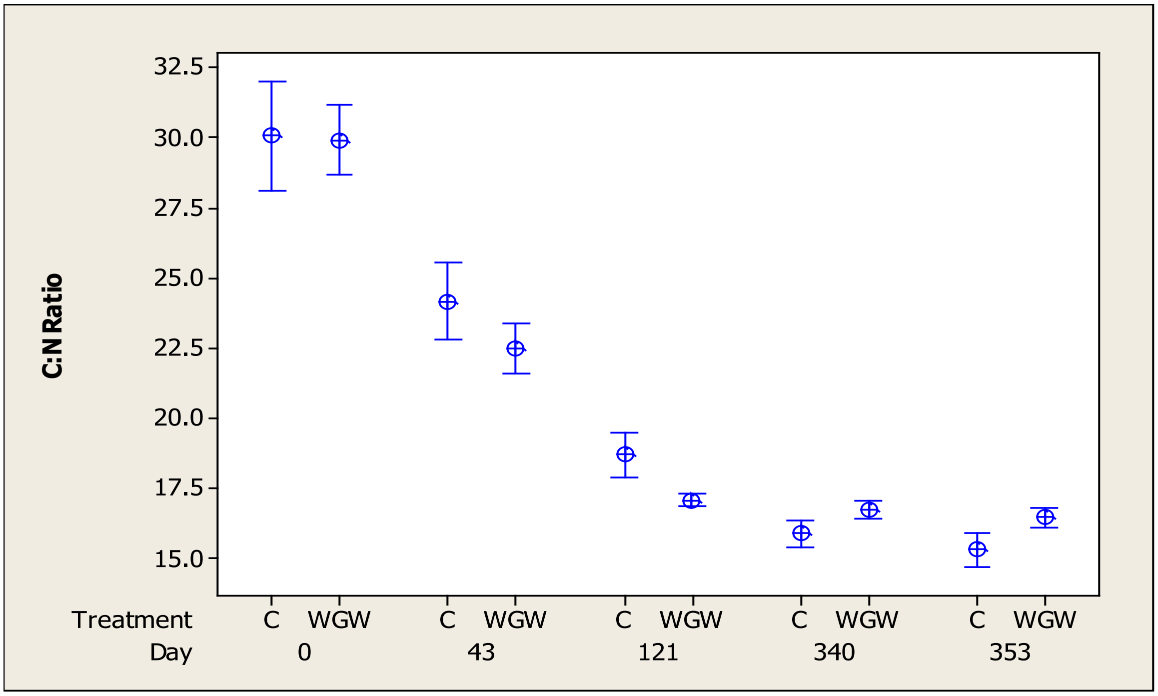

Figure 4.5 Average Change in C:N Ratio with Time, by Treatment

4.3.4.6 Total Sulphur

The total sulphur content of the WGW compost treatment was higher than the control mainly due to the gypsum (calcium sulphate) in the wallboard (Table 4.13). At the initial sampling, the sulphur concentration of the WGW compost treatment was 4.5 times that in the control treatment. By the final sampling this difference had increased to the WGW compost treatment having 10 times the amount of sulphur than the control compost treatment. The sulphur concentration in the control treatment increased from 0.38% in the initial compost to 0.71% by the third sampling after which it decreased to 0.26% by the final sampling. The WGW compost treatment increased from 1.71% at the initial sampling to 2.39% at the second sampling after which no significant change in sulphur concentration was recorded.

Table 4.13 Average Total Sulphur (%) Content in Compost Treatments (WGW vs. Control) over the Study Period.

Treatment	**Total Sulphur (%)** †				
	Day				
	0	46	123	310	353
Control	0.38	0.54	0.71	0.31	0.26
	ab B	bc B	c B	ab B	a B
WGW	1.71	2.39	2.76	2.57	2.69
	a A	b A	b A	b A	b A

†Numbers with the same lower case letters across the row and the same upper case letters within each column are not significantly different

4.3.4.7 Total Metals

The initial and final total heavy metal concentrations for the two treatments are shown in Table 4.14. The initial heavy metal concentration was dependent on the feedstocks used to prepare the treatment as indicated previously in the discussion on feedstocks. The WGW treatment had a higher initial concentration of cadmium, cobalt and lead. The control treatment had a higher initial concentration of chromium. Copper, nickel and lead concentrations were similar in two treatments at the initial sampling. These same relationships were also indicated for the two treatments at the final sampling for cadmium, cobalt, chromium, and lead. Copper and zinc had higher concentrations in the control treatment than the WGW treatment at the final sampling. Nickel had a higher concentration in the WGW treatment at the final sampling.

Table 4.14 Average Compost Treatment Initial and Final Total Heavy Metal Concentrations

	Heavy Metal Concentration (Dry basis mg kg^{-1})†¥						
Treatment	**Cd**	**Co**	**Cr**	**Cu**	**Pb**	**Ni**	**Zn**
Initial							
Control	0.1 bA	1.8 bB	38.4 aA	11.1 aB	3.5 bA	6.0 aB	57.7 aB
WGW	0.6 aB	4.5 aB	12.7 bA	9.8 aB	10.9 aA	8.8 aB	45.6 aB
Final							
Control	0.2 bA	3.4 bA	30.1 aA	31.7 aA	4.2 bA	9.3 bA	89.5 aA
WGW	0.9 aA	6.6 aA	18.4 bA	24.7 bA	14.3 aA	13.6 aA	67.5 bA

† Dry weight basis

¥ Numbers with the same lower case letters across the row and the same upper case letters within each column are not significantly different

As the overall mass of the compost piles decreased over the length of the study (control 49.9%, WGW 38.3%) , an increase in concentration of heavy metals would be expected. This was evident for cobalt, copper, nickel, and zinc for both treatments. No change in concentration was indicated for chromium or lead for both treatments over the length of the study. While there was no change in cadmium concentration from initial to final sampling for the control treatment, there was an increase in the WGW treatment.

4.3.4.8 Bioavailable Metals

At the initial sampling, the concentration of bioavailable cadmium, cobalt, chromium, lead, and nickel was higher in the WGW treatment than the control treatment (Table 4.15). Bioavailable copper and zinc were similar in both treatments at the initial sampling. The same relationships were indicated at the final sampling for cadmium, cobalt, chromium, lead, and nickel. Bioavailable copper concentration was higher in the final sample for the WGW treatment compared to the control treatment. The reverse was indicated for zinc, were the control treatment concentration was higher than the WGW treatment. Bioavailable cadmium and zinc increased in both treatments from initial to final sampling. There was no change in the concentration of bioavailable chromium, copper, lead and nickel for both treatments. Bioavailable cobalt increased in the control treatment but not the WGW treatment. Overall, at the final sampling, the WGW treatment had twice the concentration of bioavailable cadmium, cobalt, chromium and nickel compared to the control treatment. Bioavailable level concentration in the WGW treatment was more than four times that of the control treatment.

Table 4.15 Average Compost Treatment Initial and Final Bioavailable Heavy Metal Concentrations

	Heavy Metal Concentration (Dry basis mg kg^{-1})†¥						
Treatment	**Cd**	**Co**	**Cr**	**Cu**	**Pb**	**Ni**	**Zn**
Initial							
Control	0.2 bB	0.6 bB	0.4 bA	5.0 aA	0.9 bA	1.2 bA	34.6 aB
WGW	0.5 aB	2.1 aA	0.7 aA	5.0 aA	4.3 aA	2.6 aA	32.1 aB
Final							
Control	0.3 bA	0.9 bA	0.4 bA	3.4 bA	0.7 bA	1.0 bA	51.9 aA
P-WGW	0.6 aA	2.2 aA	0.9 aA	4.8 aA	4.2 aA	2.4 aA	41.2 bA

† Dry weight basis
¥ Numbers with the same lower case letters across the row and the same upper case letters within each column are not significantly different

4.4 DISCUSSION

The following section will discuss in detail the findings from this study with references to other similar studies and their findings.

4.4.1 Temperature

The addition of WGW to the compost in this study appeared to have a slight dampening effect on the initial rise to thermophillic temperatures when compared to the control treatment. Once the temperature began to rise in the WGW compost it did so at the steady rate and kept at an elevated temperature longer than the control treatment. The WGW treatment did not however reach the maximum temperature achieved by the control compost. This may have been due to the lower carbon content of the WGW compost (33.2%) compared to the control compost (40.1%). After the first remixing the WGW compost achieved a higher temperature than the control compost but had a more rapid decline than the control treatment. An increase in temperature is an indicator that microorganisms are breaking down the organic substrate as their metabolic process results in heat evolution (Liang et al., 2003). The CCME Compost Guidelines (2005) maintain that windrow compost should be kept above 55°C for a minimum of 15 days to reduce the risk to humans from organic pathogens. Both treatments maintained this temperature in excess of 20 days prior to the first re-mixing therefore meeting this important guideline.

4.4.2 Composting Parameters

The addition of WGW to compost did not have a significant effect on the final compost pH compared to the control. Both treatments started slightly acidic and ended by slightly basic. The control compost had a decline in pH from initial sampling to the first remix (6.9 to 6.2). This is similar to results found by Greenway and Song (2002) who stated that humification and consumption of organic acids by composting microorganisms tend to lower the pH initially. The WGW treatment did not experience this decline in pH but exhibited an increase in pH from start to finish. This would have implications for the heavy metals in the compost as a higher pH would make the heavy metals less available (Smith, 1999).

The WGW treatment had a higher EC than the control compost through the study until the final sampling when they were similar. Both treatments had a final EC that was significantly higher than the initial values. These compost treatments were kept in covered storage for the length of the study so were not overly affected by environmental conditions except for ambient temperature. The lack of precipitation onto the piles would therefore not leach salts out of the compost as was the issue in the previous lysimeter compost study. The compost piles did have a reduction in mass, thus the same total amount of salts in a smaller mass would equate to a higher EC concentration in the piles as the study progressed. This lack of leachable water was also indicated by the need to add water during the first two re-mixings of the compost.

Chloride concentration increased in both treatments from the initial values until the mid-point of the study. From there to the end of the study the control treatment maintained a steady chloride concentration while the WGW treatment had a decline. This would suggest a loss of chloride from the WGW compost. This loss could not be explained because both treatments were under the same environmental conditions. As there were two consecutive samples with lower chloride concentrations, it was unlikely to be a testing error.

Although both treatments had similar reductions in the C:N ratio, the WGW treatment appeared to decline faster than the control treatment. The carbon content of the WGW compost was lower than the control treatment which may have had an influence on this trend. The paper in the WGW was also a fairly simple carbon source which could lead to its rapid degradation. The two treatments did however have similar reductions in the tital mass of carbon. Greenway and Song (2002) stated that as a compost approaches maturity, the C:N ratio should be approaching 12. In this study the final C:N ratios were 15.3 and 16.4 for the control and WGW treatments respectively. Maturation testing conducted on the final compost sample appeared to indicate that both treatment composts were very stable. However, by Greenway and Song's (2002) definition, these composts would not be completely mature. This lack of maturity was also indicated by the temperature gain of both composts after the final re-mixing, especially the control treatment. This has ramifications on the bioavailability of heavy metals as the more mature (or decomposed) composts are the more tightly bound the metals become (Smith, 2009; Businelli et al., 2009).

4.4.3 Total Sulphur

Total sulphur content increased in the WGW treatment over the length of the study. Initially the WGW treatment had a total sulphur content 4.5 times that of the control treatment which increased to a factor of 10 by the end of the study. As the mass of the piles decreased due to the composting process during the study, the overall mass of calcium sulphate in the pile would be the same from start the finish, the ratio of calcium sulphate in relation to the overall mass of the pile would increase. The higher sulphur content of the WGW treatment could have an influence on the bioavailability of heavy metals as Vink (2010) reported that the addition of gypsum (calcium sulphate) encourages the formation of metal sulphides thereby taking the metals out of solution. This was not true for all metals as zinc and cadmium concentrations in pore space water actually increased (Vink, 2010).

4.4.4 Total Heavy Metals

Cobalt, copper, nickel and zinc increased in concentration from initial to final sampling for both compost treatments. Cadmium increased in the WGW treatment but not the control. Cadmium was in very low concentration in the control treatment, therefore variability in analysis could have had an effect. There was no change in chromium or lead concentration from initial to final sampling for both treatments. Without leaching from the compost piles, the total mass of heavy metals would remain constant (assuming no loss by vaporization) but due to mass loss by the compost pile, there would be an increase in heavy metal concentrations (Eneji et al., 2003). The mass loss was greater for the control treatment at 50% while the WGW treatment had a loss of 38%. In the final sampling, the WGW treatment had higher concentrations of cadmium, cobalt, lead, and nickel, while the control treatment had higher concentrations of chromium, copper, and zinc. These differences can be explained by the metal concentrations of the feedstock materials.

4.4.5 Total Bioavailable Metals

Both treatments recorded an increase in the concentration of bioavailable cadmium and zinc from initial sampling to final sampling. As with the total metals, the WGW treatment had a higher concentration of bioavailable cadmium while there was a higher concentration of bioavailable zinc in the control treatment. In both treatments, almost the entire total amount of cadmium was bioavailable while only about two-thirds of the total zinc was bioavailable. The higher concentration of bioavailable cadmium in the WGW treatment was consistent with the findings of Vink (2010). Brusinelli et al. (2009) found that although the cadmium concentration in compost is low, it tends to be mobile. Das and Kirkland, (2008) found that cadmium was more available as the compost aged. Smith (2009) stated that zinc was commonly reported as the most labile heavy metals in compost. Kumpiene et al. (2008) found that the mobility of zinc can be increased with the addition of organic matter.

Vink (2010) found that the addition of gypsum tended to decrease the availability of copper and lead. While the availability of copper and lead was higher in the WGW treatment than the control treatment, there was no reduction in the availability of these two heavy metals in the WGW treatment from initial to final sampling. This is in contrast to Vink's findings as there would have been an expected decrease in concentration.

Approximately one-third of the total concentration of lead and cobalt was bioavailable. Smith (2009) stated that lead had a high affinity for the sulphide and residual fractions of compost and therefore have a low availability. Kumpiene et al. (2008) found that calcium compounds can immobilize lead.

Chromium and nickel were the lowest with approximately one-tenth of the total concentration of these heavy metals being bioavailable. This was expected with chromium as it is usually in the (VI) form in aerobic conditions and has a low bioavailability. Wauna and Okieimen (2011) found that nickel forms a stable precipitate nickelous hydroxide in slightly alkaline solutions as was found in the final composts of both treatments. These nickel precipitates will then adsorb to soil particles and become immobile.

4.5 CONCLUSION

Overall, the use of WGW as a compost additive did not negatively affect the composting process. WGW addition to compost did not prevent the compost from meeting regulatory temperature guidelines. Carbon to nitrogen ratio reduction was found to be similar to a horse bedding / hay compost in this study. No significant differences were found in pH and electrical conductively between the final composts for the two treatments. The WGW treatment was found to have a much higher total sulphur concentration that could prove beneficial for sulphur-deficient soils. The high mineral content of the WGW compost led to a much lower overall mass loss but this did not seem to affect the compost substrates' decomposition. The WGW treatment did have higher cadmium and lead concentrations but were still well below the CCME Class A guideline. If there was concern with other feedstocks containing these metals the amount of WGW could be reduced.

CHAPTER 5 CONCLUSIONS

This study looked at the use of waste gypsum wallboard as a compost additive in three studies under very different conditions. The in-vessel study produced a short-term mechanically prepared compost. The lysimeter cell study looked at potential movement of compost constituents from compost to soil to water under a static compost system open to the ambient environmental conditions. The final study evaluated the performance of compost with the addition of waste gypsum wallboard in a protected large-scale process similar to industrial operations.

All three studies provided valuable information both about the performance of waste gypsum wallboard in a compost system as well as areas of potential concern. Primarily, in the feedstock characterization, it was found that papered WGW had a higher lead concentration than de-papered WGW. This may have been due to the use of lead based paints used in the latter part of the twentieth century in Nova Scotia. However, this was not found to increase the lead concentration in compost over the CCME recommended guideline at a 34% addition rate (on a dry basis) to straw/horse bedding/biosolids compost. This would indicate that if WGW was added to compost at this level or lower there would not be a concern about lead concentrations in the compost

Waste wallboard gypsum addition did not impede the compost from reaching high enough temperatures to meet regulatory limits at an 18% addition rate. Although it was found that at 34% addition level, papered WGW compost reached higher temperatures than de-papered WGW compost. Waste Gypsum Wallboard was not found to have significant effect on compost carbon reduction compared to non-WGW compost in this study. Final compost pH and electrical conductivity were also found to be similar in WGW and non-WGW composts.

Results did indicate that the addition of WGW to compost would increase the concentration of total cadmium and that there was the potential for cadmium to be more bioavailable where using WGW in compost. The addition of waste gypsum wallboard to compost would increase the concentration of total sulphur in the compost. This could be beneficial for crops that required sulphur (e.g. canola, corn, alfalfa) or to amend sulphur deficient soils.

Recommendations include a comprehensive plant germination and crop performance study to be conducted in the future. This would develop a full suite of knowledge on the suitability of waste gypsum wallboard as a compost additive, especially considering the potential high sulphate concentration.

BIBLIOGRAPHY

Baldwin, K. And Sheldon, J. 1999. Availability of heavy metals in compost-amended soils. Bio. Tech. 69: 1-14.

Businelli, D., Massaccesi, L., Said-Pullicino, D., and Gigliotti, G. 2009. Long-term distribution, mobility and plant availability of compost-derived heavy metals in a landfill covering soil. Sci. Total. Environ. 407(4): 1426-35.

Canadian Council of Ministers of the Environment. 2005. Guidelines for Compost Quality. PN1340. Winnipeg, Manitoba, Canada.

Carter, M. 1993. Soil Sampling and Methods of Analysis. Canadian Society of Soil Science. CRC Press. Boca Raton, FL, U.S.A.

Certain Teed. 2011a. What is gypsum wallboard? www.certainteed.com/learning-center/gypsum/?qid=123. Verified October 1, 2012.

Certain Teed. 2011b. What is fire rated gypsum? www.certainteed.com/learning-center/gypsum/?qid=124. Verified October 1, 2012.

Chen, G., Zeng, C., Du, C., Huang, D., Tang, L., Wang, L., and Shen, G. 2010. Transfer of heavy metals from compost to red soil and groundwater under simulated rainfall conditions. J. Haz. Mat. 181: 211-216.

Composting Council Research and Education Foundation. 2002. Test methods for the evaluation of compost quality (TMECC). US Composting Council. Bethesda, MD, U.S.A.

Das, K., and Kirkland, J. 2008. Quantification of water extractable contaminants from food waste and biosolids blends at different stages of composting. Com. Sci. Util. 16(3): 200-206.

Dillon Consulting Ltd. 2006. Final Report. Construction & Demolition Debris Management Study for the Nova Scotia Department of Environment and Labour and the Resource Recovery Fund Board.

Dontsova, K., Lee, Y.B., Slater, B.K., and Bigham, J.M. 2005. Gypsum for agricultural use in Ohio – Sources and quality of available products. Ohio State University Extension Fact Sheet. ANR-20-05. Columbus, Ohio, U.S.A.

Dougherty, M. 1999. Field Guide to On-Farm Composting. Natural Resource, Agriculture, and Engineering Service. Ithaca, New York, U. S. A.

Eneji, A.E., Honna, T., Yamamoto, S., Masuda, T., Endo, T., and Irshad, M. 2003. The relationship between total and available heavy metals in composted manure. J. Sustain. Agri. 23(1): 125-134.

Environmental Protection Agency. 2000. Bioaccumulation testing and interpretation for the purpose of sediment quality assessment. EPA-823-R-00-001. Washington, DC, U.S.A.

Farrell, M., and Jones, D.L. 2009. Heavy metal contamination of mixed waste compost: metal speciation and fate. Bioresour. Technol. 100: 4423-4432.

Founie, A. 2006. Gypsum. Mineral Commodity Summaries. US Geological Survey. Reston, VA, U.S.A.

Flynn, B. 1998. Invisible threat, odors and landfill gas from C&D waste. Waste Age, 29: 91-97.

Gratton, R., and Beaudoin, G. 2010. Gypsum Recycling in the National Capital Region. National Recycling Initiative. Ottawa, Canada.

Greenway, G.M. and Song, Q.J. 2002. Heavy metal speciation in the composting process. J. Environ. Mon..4:300-305.

Gypsum Association. 2004. Gypsum panel, products types, uses, sizes, and standards. www.gypsum.org/wp/wp-content/uploads/2011/11/223-04.pdf. Verified October 1, 2012.

Gyspum Association. 2008. Gypsum sustainability. www.gypsumsustainability.org/recycled.html. Verified December 6, 2013.

Gypsum New Zealand. 2013. Soil improvement. http://www.gypsum.co.nz/pages/product/soil.php Verified December 8, 2013.

Hanay, A., Buyuksonmez, F., Kiziloglo, F. M., and Conbolat, M.Y. 2004. Reclamation of saline-sodic soils with gypsum and MSW compost. Compost Sci. & Util. 12(2): 175-179.

Hargreaves, J., Adl, M., and Warman, P. 2008. A review of the use of composted municipal solid waste in agriculture. Sci. Direct. 123: 1-14.

Health Canada, 2013. Lead and Human Health. http://www.hc-sc.gc.ca/hl-vs/iyh-vsv/environ/lead-plomb-eng.php. Verified September 9, 2013.

Kairies,C.L., Schroeder, K.T., and Cardone, C.R. 2006. Mercury in gypsum produced by flue gas desulfurization. Fuel 85: 2530-2536.

Khan, E., Khaodhir, S., and Ruangrote, D. 2009. Effects of moisture content and initial ph in composting process on heavy metal removal characteristics of grass clipping compost used for stormwater filtration. Biores. Tech. 100: 4454-4461.

Kumpiene, J; Lagerkvist, A; and Maurice, C. 2008. Stabilization of As, Cr, Cu, Pb, and Zn in soil using amendments – a review. Waste Manage. 28 (1): 215 – 25.

Liang, C., Das, K., and McClendon, R. 2003. The influence of temperature and moisture contents regimes on the aerobic microbial activity of a biosolids composting blend. Biores. Tech. 86: 131-137.

Lorrimore, L. 2009. FGD gypsum overview: production, handling and use. Presented at Agicultural uses of FGD gypsum workshop, November 17-19, 2009. Indianapolis, IN, U.S.A.

Mandepanda, U., Kalyanam, D., Madabhushanam, M., Fu, H., and Suri, R. 2000. Reuse of Waste Materials for Manure Odor Mitigation and Phosphorous Fixation. Proceedings of the International Conference on Waste Technology and Management. Pg 487-496.

Marvin, E. 2000. Gypsum wallboard recycling and reuse in the state of Vermont. Vermont Agency of Natural Resources. Waterbury, VT, U.S.A.

Northeast Waste Management Officials' Association. 2010. Promoting Greater Recycling of Gypsum Wallboard from Construction and Demolition (C&D) Projects in the Northeast. Boston. U.S.A.

Nova Scotia Department of the Environment. 2010. Compost Facility Guidelines. Halifax, NS, Canada.

Paré, T., Dinel, H., and Schnitzer, M. 1999. Extractability of trace metals during co-composting of biosolids and municipal solids wastes. Biol. Fertil. Soils. 29: 31-37.

Rynk, R. 1992. On-Farm Composting Handbook. NRAES. Ithaca, NY, USA.

Saludes, R.B., Iwabuchi, K., Miyatake, F., Abec, Y., and Honda, Y. 2008. Characterization of dairy cattle manure/wallboard paper compost mixture. Bioresour. Technol. 99(15): 7285-90.

SAS Institute Inc. 2010. SAS/STAT for statical analysis v 9.3. Cary, NC, USA.

Shock, S. S., Noggle, J. J., Bloom, N., and Yost, L. J. 2009. Evaluation of potential for mercury volatilization from natural and FGD gypsum products using flux-chamber tests. Environ.Sci.Technol.43:2282-2287.

Smith, S.A. 2009. A critical review of bioavailability and impacts of heavy metals in municipal solid waste composts compared to sewage sludge. Environ. Int.. 35: 142-156.

Tayibi, H. Choura, M., Lopez. F.A., Alguacil, F. J., and Delgado, A. 2009.Environmental impact and management of phosphogypsum. J. Environ. Man. 90: 2377-2386.

Tisdale, S.L.; Nelson, W. L.; Beaton, J. D.; and Havlin, J.L. 1993. Soil Fertility and Fertilizers. Fifth Edition. MacMillian Publishing Company.New York, New York, U.S.A.

Turley. W. 1998. What's happening in gypsum recycling. C&D Debris Recycling. 5(1): 8-12.

Varcoe, J. van Leeuwenb, J.A., Chittleborough, D.J., James W. Cox, J.W., Smernik, R.J., and Heitz, A. 2010. Changes in water quality following gypsum application to catchment soils of the Mount Lofty Ranges, South Australia. Org. Geochem.41(2): 116-123.

Vink, J.P.M., Harmsen, J., and Rijnaarts, J. 2010. Delayed immobilization of heavy metals in soils and sediments under reducing and aerobic conditions; consequences for flooding and storage. J. Soil Sed. 10: 1633-1645.

Warman, P.R., Muizelarr, T., and Termeer, W.C. 1995. Bioavailability of As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Se, and Zn from biosolids amended compost. Compost Sci. 3(4): 40-50.

Wauna, R. and Okieimen, R. 2011. Heavy metals in contaminated soils: a review of sources, risks, and best available strategies for remediation. ISRN Ecology. Vol. 2011. Article 402647.

Webb, K.T., Thompson, R.L., Beke, G.J., and Nowland, J.L. 1991. Soils of Nova Scotia, Report No. 19. Agriculture Canada. Ottawa, Ontario, Canada.

Wolkowski, R.P. 2003. Using recycled wallboard for crop production. University of Wisconsin, Madison, WI, U.S.A.

Zia,M.H., Sabir, M., Ghafoor, A., and Murtaza, G. 2007. Effectiveness of sulphuric acid and gypsum for reclamation of a calcareous saline-sodic soil under four crop rotations. J. Agro. Crop Sci. 193 (4): 817-825.

APPENDIX

Table A.1 Lysimeter Cell Study Compost Treatments Initial and Final pH

Compost Treatment pH					
Control		P-WGW		D-WGW	
Initial	Final	Initial	Final	Initial	Final
7.6	6.8	7.1	6.7	6.9	6.6

Table A.2 Lysimeter Cell Study Compost Treatments Initial and Final Electrical Conductivity

Compost Treatment Electrical Conductivity					
Control		P-WGW		D-WGW	
Initial	Final	Initial	Final	Initial	Final
------------ dS m^{-1} ------------					
4.57	3.30	7.05	4.64	6.32	4.17

Table A.3 Lysimeter Cell Study Compost Treatments Initial and Final Chloride Concentration

Compost Treatment Chloride Concentration					
Control		P-WGW		D-WGW	
Initial	Final	Initial	Final	Initial	Final
------------ mg kg^{-1} ------------					
516	210	334	195	282	159

Table A.4 Lysimeter Cell Study Compost Treatment Initial and Final Total Heavy Metal Concentrations and CCME Class A Compost Guidelines

Heavy Metal	Heavy Metal Concentration†						
	Control		P-WGW		D-WGW		CCME
	Initial	Final	Initial	Final	Initial	Final	Class A
	mg kg^{-1}						
Cd	0.4	1.2	1.8	2.7	2.2	1.5	3
Co	3.2	6.8	7.9	10.7	9.1	11.6	34
Cr	25.9	34.8	11.2	19.5	10.7	19.3	210
Cu	85.7	119	54.9	52.9	62.1	74.9	400
Ni	8.1	19.4	8.9	17.6	10.2	20.1	62
Pb	29.7	49.9	54.0	48.2	40.2	49.5	150
Zn	156	213	96	115	108	119	700

† Dry weight basis

Table A.5 Lysimeter Cell Study Compost Treatments Initial and Final Bioavailable Heavy Metal Concentrations

Heavy Metal	Heavy Metal Concentration†					
	Control		P-WGW		D-WGW	
	Initial	Final	Initial	Final	Initial	Final
	mg kg^{-1}					
Cd	0.3	0.4	0.6	1.3	0.7	0.8
Co	0.7	0.8	1.0	1.4	1.9	1.7
Cr	0.4	0.2	1.1	1.3	1.4	1.5
Cu	24.0	20.5	22.0	16.7	19.8	15.3
Ni	1.4	0.9	2.0	1.8	2.7	2.2
Pb	7.4	9.6	8.5	11.8	14.2	13.1
Zn	100	134	73	89	73	88

† Dry weight basis

Table A.6 Lysimeter Cell Study Compost Treatment Initial and Final Total Carbon Content

Compost Treatment Total Carbon Content					
Control		P-WGW		D-WGW	
Initial	Final	Initial	Final	Initial	Final
%					
37.8	35.3	23.8	20.0	25.8	21.5

Table A.7 Lysimeter Cell Study Compost Treatment Initial and Final Total Nitrogen Content

Compost Treatment Total Nitrogen Content					
Control		P-WGW		D-WGW	
Initial	Final	Initial	Final	Initial	Final
%					
1.8	2.1	1.1	1.2	1.1	1.3